

## Appendix 3: Recent Ecosystem Changes in the Gulf of Alaska

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### Summary

*Evidence suggests that there were climate regime shifts in 1977, 1989, and 1998 in the North Pacific. Ecosystem responses to these shifts in the Gulf of Alaska (GOA) were strong after the 1977 shift, but weaker after the 1989 and 1998 shifts. Variation in the strength of responses to climate shifts may be due to the geographical location of the GOA in relation to the spatial pattern of climate variability in the North Pacific. Prior to 1989, climate forcing varied in an east–west pattern, and the GOA was exposed to extremes in this forcing. After 1989, climate forcing varied in a north–south pattern, with the GOA acting as a transition zone between the extremes in this forcing. The 1989 and 1998 regime shifts did not, therefore, result in strong signals in the GOA.*

*There were both physical and biological responses to all regime shifts in the GOA. However, the primary re-organization of the GOA ecosystem occurred after the 1977 shift. After 1977, the Aleutian Low intensified, resulting in a stronger Alaska Current, warmer water temperatures, increased coastal rain, and, therefore, increased water column stability. The optimal stability window hypothesis suggests that water column stability is the limiting factor for primary production in the GOA (Gargett 1997). A doubling of zooplankton biomass between the 1950s–60s and in the 1980s indicates that production was positively affected after the 1977 regime shift (Brodeur and Ware 1992). Recruitment and survival of salmon and demersal fish species also improved after 1977. Catches of Pacific salmon, recruitment of rockfish (Pacific ocean perch), and flatfish (arrowtooth flounder, halibut, and flathead sole) recruitment and biomass all increased. There are indications that shrimp and forage fish, such as capelin, were negatively affected by the 1977 shift, as survey catches declined dramatically in the early 1980s (Anderson 2003). Availability of forage fish may have been related to the decline in marine mammal and seabird populations observed after the 1977 shift (Piatt and Anderson 1996).*

*After 1989, water temperatures were cooler and more variable in the coastal GOA, suggesting that production may have been lower and more variable. After 1989, British Columbia (B.C.) salmon catches and survival were low and Queen Charlotte Island (northern B.C.) herring declined. Salmon catches in Alaska, however, remained high. Groundfish biomass trends which began in the early 1980s continued, with increases in flatfish biomass. By the late 1980s, arrowtooth flounder, rather than walleye pollock, were dominant. Large groundfish biomass estimates resulted in negative recruit per spawning biomass anomalies of demersal fish.*

*There is some indication that the GOA ecosystem may have weakly responded to the 1998 regime shift. Increased storm intensity from 1999 to 2001 resulted in a deeper mixed layer depth in the central GOA, and coastal temperatures were average or slightly below average. After 1998, coho survival increased in southern B.C., shrimp catches increased in the northern GOA, and the 1999 year class of both walleye pollock and Pacific cod was strong in the northern GOA. Recruitment information from longer-lived species will be available in the near future, enabling scientists to determine if there were other responses to the 1998 climate shift.*

*It is apparent that many components of the GOA ecosystem respond to decadal-scale variability in climate and ocean dynamics. It is unknown if changes observed after the 1998 shift will persist in the GOA and how long the current conditions in the GOA will last. Predicting regime shifts will be difficult until the mechanisms that cause the shifts are understood (Minobe 2000). Monitoring indicator species is one method to improve our knowledge of the mechanisms that cause the shifts. Potential indicator species of regime shifts would include those which have a short life-span, are sensitive to changes, are key trophic groups, and/or are targeted by fisheries which produce data that are readily available. Examples of potential indicator species in the GOA that fit some of these criteria include sockeye and pink salmon, juvenile fish abundance, ichthyoplankton, as well as zooplankton biomass and composition.*

### **A3.1 Introduction**

In this section we examine biological changes in the Gulf of Alaska (GOA) system, which is here defined to include coastal waters of northern British Columbia (B.C.), southeast Alaska, central Alaska and the central GOA. Atmospheric processes that influence the central GOA, particularly seawater temperatures as measured along Line-P, are reported in Section 1 (Subsections 1.2 and 1.3). Also reported in Section 1 are recent oceanographic changes in the Alaskan Coastal Current, the Alaska Current and Alaskan Stream, the central and northern GOA and northern B.C. Though data are limited, some recent nutrient and chlorophyll *a* concentration data were available and presented in this section. We provide zooplankton biomass data for the Alaskan Shelf and in the Alaskan Gyre. Survey catch per unit effort (CPUE) of pandalid shrimp is given. Where available, data are presented for catch, CPUE, recruitment, biomass, recruit per spawning biomass, and/or growth for pelagic fishes (Pacific herring, capelin, and eulachon), gadids (walleye pollock and Pacific cod), sablefish, flatfish (arrowtooth flounder, flathead sole, and Pacific halibut), and rockfish (Pacific ocean perch and yellowtail rockfish). In stocks that are abundant, the relationship between recruits and spawners may not be linear, *i.e.*, density-dependent factors may limit recruitment. Under these circumstances, the pattern of recruits per spawner will appear as an inverse of the spawning biomass because annual rates of production have leveled off. For this reason, we present both recruitment and recruits per spawner. Marine mammal and seabird information is also included.

### **A3.2 Physical Oceanography**

Long-term hydrographic conditions in the GOA

are based primarily on sampling at the GAK1 station near the mouth of Resurrection Bay, along Line-P extending west from the mouth of Juan de Fuca Strait, and at British Columbia coastal lighthouses. These are detailed in Section 1 (Decadal-scale Climate Events).

Water column temperature and salinity in the northern GOA respond to seasonal changes in heat flux, freshwater input and winds, but substantial long-term variability is evident over the past several decades. A significant amount of temperature variance is at the 5-year period. Before 1977, the upper water column was anomalously cool and near-surface waters were anomalously saline. Conditions after 1977 alternated between warm fresh and cold saline waters. The largest warm event occurred in association with the strong 1997–98 El Niño. These anomalies are advected into the region, rather than locally forced by winds, runoff, heating and cooling (Royer, in press). Sea surface temperatures (SSTs) were average or below average at GAK1, and along Line-P during 1999–2002. However, summer 2002 and winter 2003 temperatures were above normal at GAK1 and below average on Line-P (PICES 2004). Temperature at most depths is positively correlated with the Pacific Decadal Oscillation (PDO). A shallowing mixed layer depth trend has been observed at Ocean Station Papa, Line-P, but not in the northern GOA.

Coastal temperatures also shifted to colder water after 1998, but this regime was interrupted by a warming in 2003, possibly a response to the 2002–03 El Niño. It is, so far, uncertain if this shift to warmer waters has continued into 2004. Coastal salinities do not reveal an El Niño impact, nor a 1998 regime shift, but do reveal a multi-decadal decline in salinity at Langara Island, (northern

Queen Charlotte Islands). The impact of this trend on nearby southeast Alaskan waters is not known.

### A3.3 Lower Trophic Levels

Despite the long-recognized high fish productivity of the northern GOA shelf, there have been few studies of the nutrient concentrations, chlorophyll (phytoplankton biomass), and primary production which support this high fish production. Production in both the oceanic and neritic regions is highly seasonal, with very low production during winter and moderate to high production during the summer. Light levels and the mixed layer depth are limiting factors of phytoplankton blooms in the winter and spring. There is an increase in phytoplankton production in the spring; the bloom is not large in oceanic regions, but it is in neritic regions. In coastal regions, the spring bloom of phytoplankton depletes surface waters of essential nutrients (primarily nitrate), therefore, spring bloom conditions are short-lived. Mixed layer depth, light levels and nutrients may vary interannually, thereby affecting production.

#### Nutrients

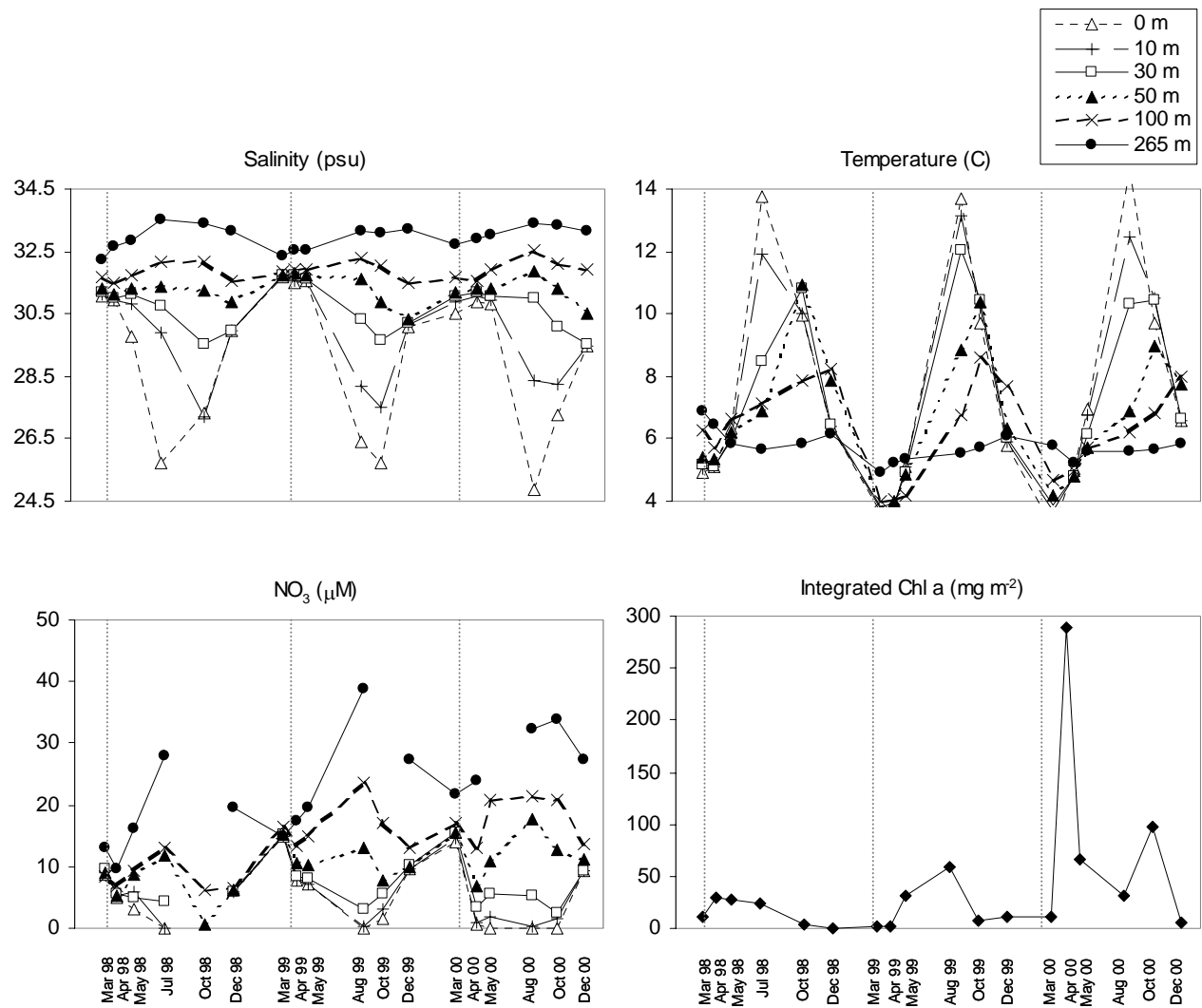
Interannual variability in nutrient concentration in the coastal GOA can be large (Childers *et al.*, in press). This is illustrated with data from GAK1 (core of the Alaska Coastal Current (ACC)) and GAK4 (located at mid-shelf) for 1998–2000 (Figs. A3.1 and A3.2). In the northern GOA, March stratification was stronger in 1998 and 2000 than in 1999, with a well mixed, saltier and cooler upper 100 m. Integrated over the entire water column, nitrate was lowest in 1998 and highest in 2000 (almost double that of 1998) at both GAK1 and GAK4. This “initial” March condition is important because it sets an upper limit on total nitrate availability for the spring bloom, since there is little (or no) replenishment of shelf nutrients in the spring, or until late fall–winter. The higher concentration of nutrients in 2000 resulted in larger phytoplankton blooms for that year (Figs. A3.1 and A3.2). Nutrient concentrations at the surface (0–10 m depth) became completely depleted in each of the 3 years, but the timing and duration of the period of depletion varied interannually and spatially (across the shelf). At GAK1, surface nutrients were

depleted by July 1998 and August 1999. However, in 2000, a year with the highest beginning nutrient levels, nutrients were depleted by April, and remained depleted through October. At GAK4, there was less interannual variability in the timing of nitrate depletion, and surface nutrient depletion was apparent in July–August. Nitrate depletion and the phytoplankton bloom occur first on the inner shelf, within the ACC and later on the middle and outer shelf. This is likely due to the early water column stabilization on the inner shelf provided by the fresher water of the ACC. At Ocean Station Papa, winter nutrient levels were low during most of the 1990s, but have increased in recent years.

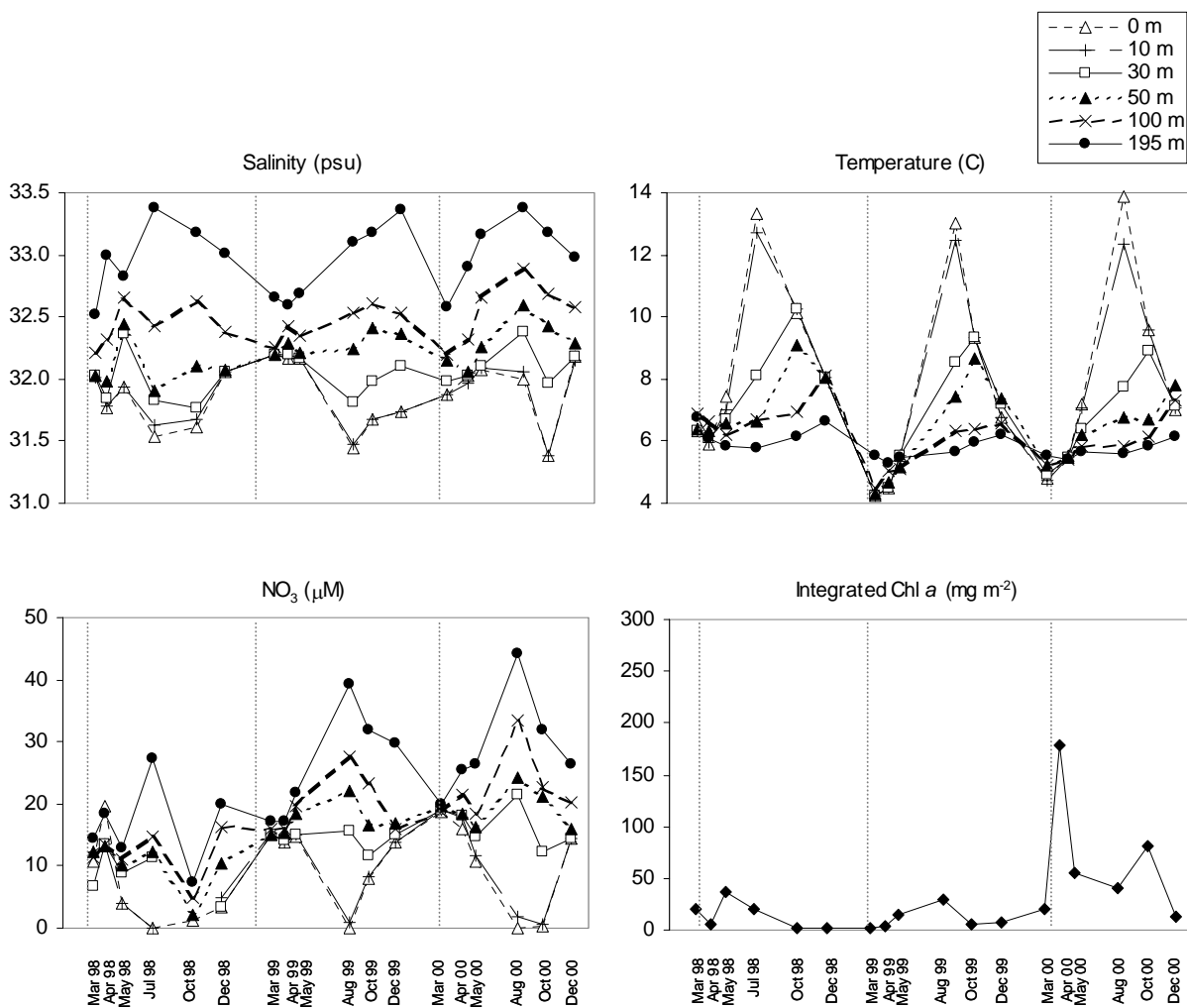
#### Phytoplankton

Chlorophyll *a* concentrations are indicative of phytoplankton biomass, and vary seasonally and interannually (Childers *et al.*, in press). For example, March chlorophyll concentrations at GAK1 were low in 1999 relative to 1998 and 2000. However, May chlorophyll concentrations were highest in 1999 relative to 1998 and 2000 (Childers *et al.*, in press, Fig. A3.3). The analysis by Childers *et al.* (in press) at GAK1 and an Empirical Orthogonal Function (EOF) analysis of SeaWiFS data for the entire GOA (Brickley and Thomas 2004) indicate that, overall, 1998 had the lowest concentrations of chlorophyll (Fig. A3.4). Also, the chlorophyll maximum was strongest in 1999 and 2000, and somewhat weaker in 2001 (Childers *et al.*, in press; Brickley and Thomas 2004). Perhaps this “interannual” difference was a reflection of a seasonal difference in which the conditions in 1999 were such that the spring bloom was delayed substantially early in spring, but later was manifested as an abnormally intense spring bloom in May. Unfortunately, we have so little data that defining “normal” is difficult, especially when one also considers the spatially patchy distributions.

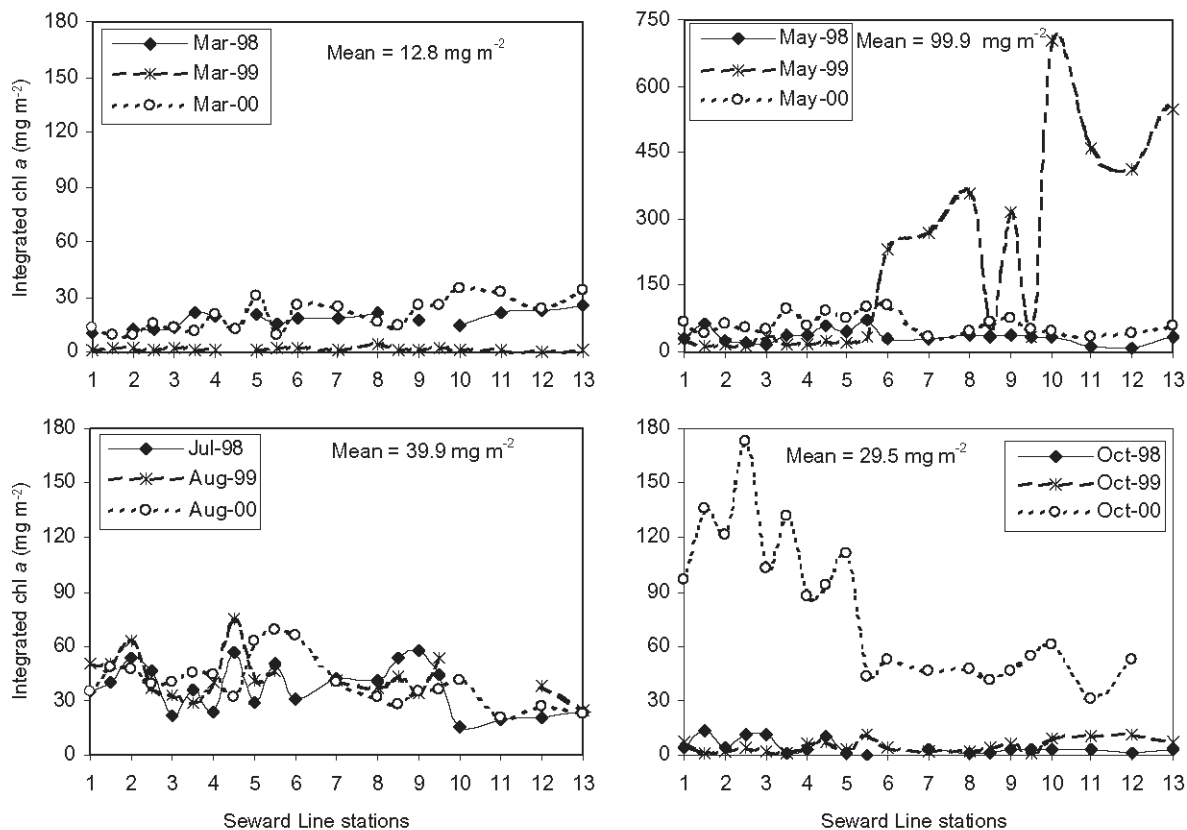
The community composition of phytoplankton may also vary interannually. For example, phytoplankton at Ocean Station Papa shifted from an autotrophic flagellate-dominated community to one consisting of over 50% coccolithophores in 2000, which were also observed in SeaWiFS data.



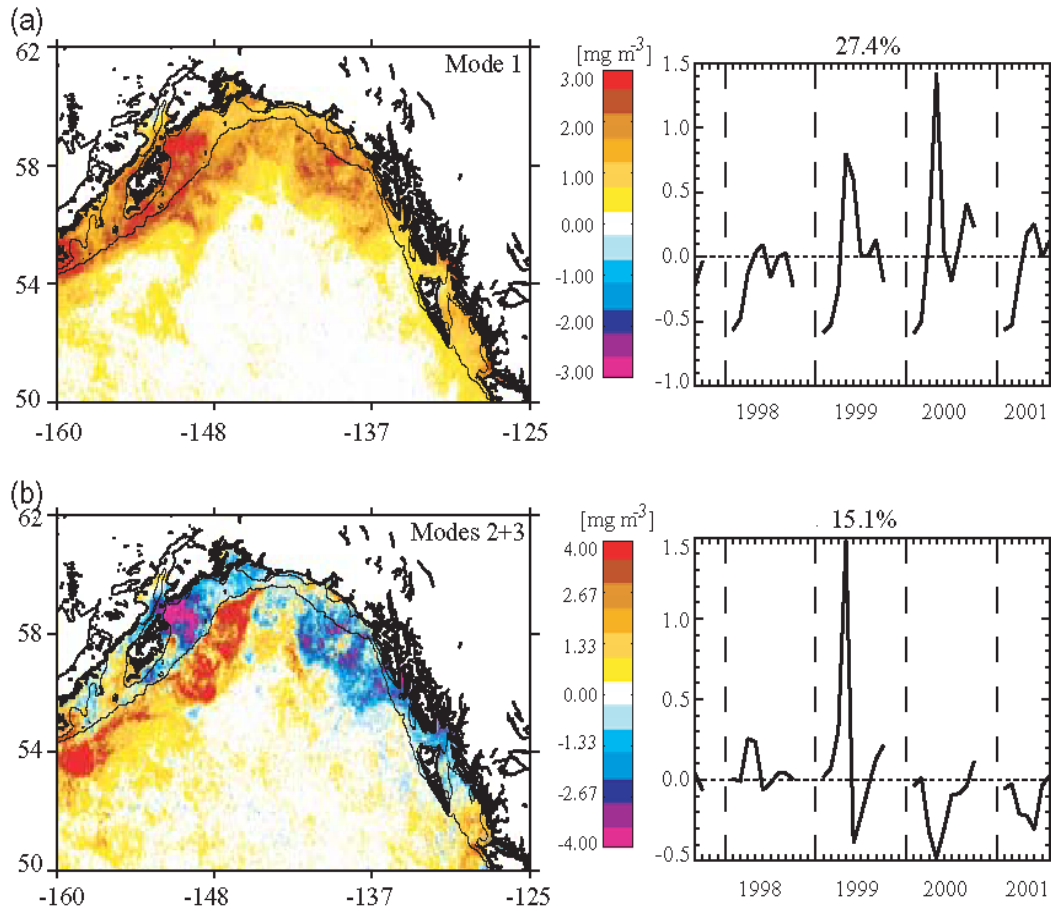
**Fig. A3.1** Time series (1998–2000) of salinity, temperature, nitrate, and integrated chlorophyll *a* concentration (0–50 m depth) at GAK1. Dashed vertical lines indicate March data (figure 11 from Childers *et al.* in press).



**Fig. A3.2** Time series (1998–2000) of salinity, temperature, nitrate, and integrated chlorophyll *a* concentration (0–50 m depth) at GAK4. Dashed vertical lines indicate March data (figure 11 from Childers *et al.* in press).



**Fig. A3.3** Vertically integrated chlorophyll concentrations (mg m<sup>-2</sup>) across the Gulf of Alaska shelf in March, May, July–August, and October of 1998–2000. Note the change in y scale for May (figure 3 from Childers *et al.* in press).

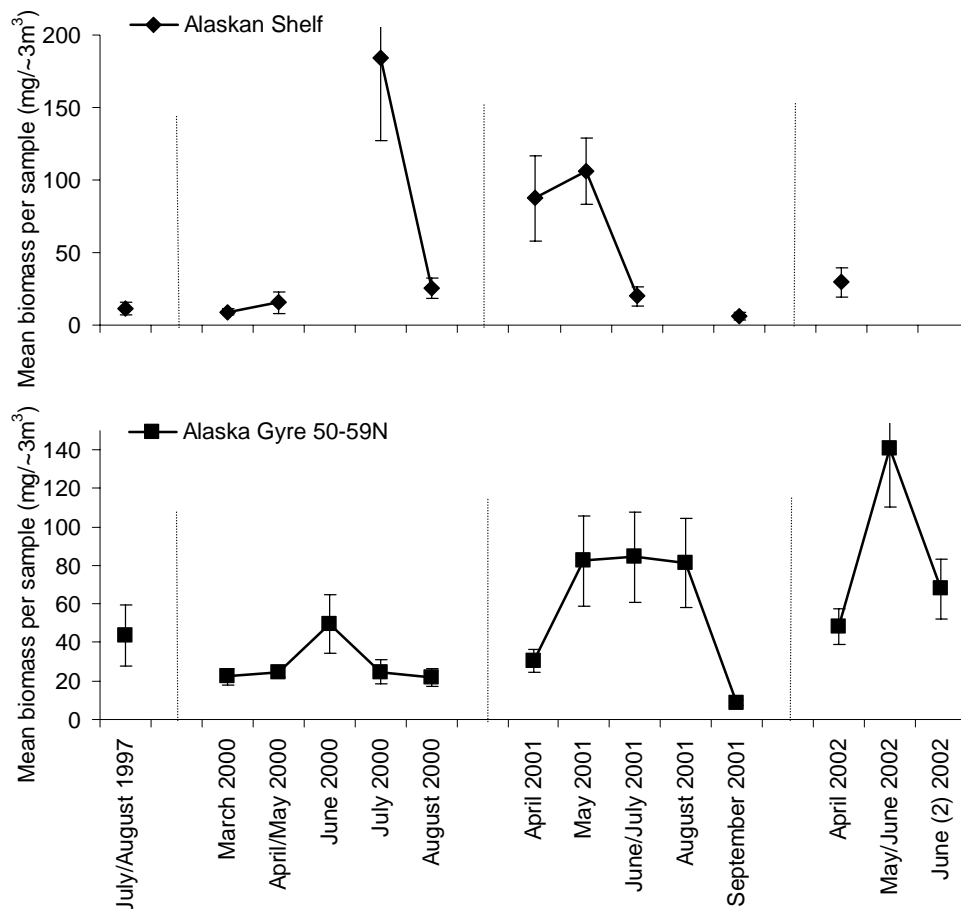


**Fig. A3.4** Empirical orthogonal function (EOF) decomposition of the monthly image time series (excluding winter, November–January) showing (a) the dominant mode (27.4% of variance) and its associated time series, and (b) the summed second and third most dominant modes (15.1% of variance) and their associated time series. The temporal mean is removed from each pixel and masking is applied to exclude pixels from the heads of major bays, fjords, and river outlets (white regions inshore of the shelfbreak in mode 1) (figure from Brickley and Thomas 2004).

## Zooplankton

Zooplankton time series data are sparse for the GOA. There is some evidence which suggests that the magnitude and timing of blooms respond to interannual and decadal-scale variability. A doubling of zooplankton biomass was observed in the subarctic Pacific between 1956–62 and 1980–89 (Brodeur and Ware 1992). Also, data from a continuous plankton recorder suggest that mesozooplankton biomass increased during 2000–02 (Fig. A3.5; PICES 2004). Observations at Ocean Station Papa indicate that zooplankton population development timing has changed on a

decadal scale: development was late in the 1970s, early in the 1990s, and average from 1999–2001 (Mackas *et al.* 1998; PICES 2004). In southern B.C. waters, the community composition of zooplankton also appears to vary on a decadal scale and may be related to changes in the ocean and climate conditions (Mackas *et al.* 2001). From 1990–98, the zooplankton assemblage was comprised of species from areas to the south (California Current) (Mackas *et al.* 2001). Changes in primary and secondary production, as well as community composition, may influence the survival of larval, juvenile, and forage fish.



**Fig. A3.5** Mean mesozooplankton biomass (estimated from abundance) from continuous plankton recorder transects sampled in 1997 and between March 2000 and summer 2002 (Sonia Batten, Sir Alastair Hardy Foundation for Ocean Science, pers. comm.). Error bars are one standard error (from PICES 2004).



### A3.4 Invertebrates

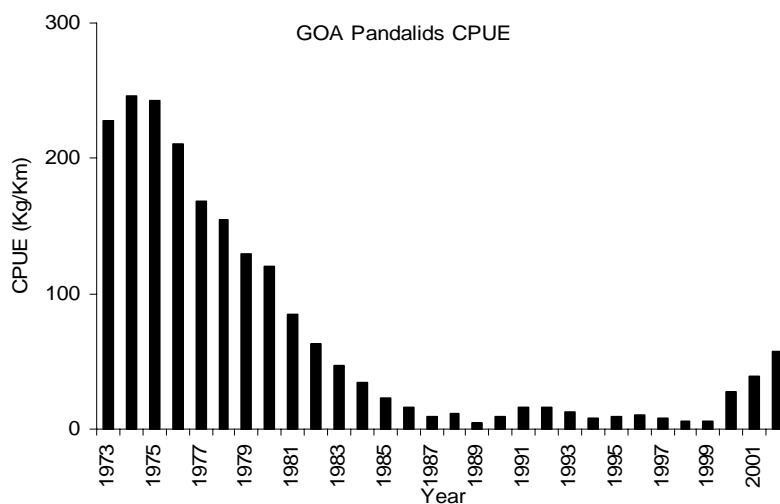
#### Shrimp

Abundance of pandalid shrimp, as sampled in small mesh surveys in the GOA, appears to vary on a decadal scale (Anderson 2003). Abundance decreased after the mid-1970s, and increased after 1998 (Fig. A3.6). Average catch per tow for all pandalids combined increased to over 75 kg km<sup>-1</sup> in 2001, and was 38.5 kg km<sup>-1</sup> in 2002. Relative pandalid shrimp abundance at this level last occurred in survey results nearly 20 years ago, in the early 1980s. The most significant recovery, among pandalid species, has occurred with *Pandalus goniurus*. This species had become almost functionally extinct in GOA shallow nearshore locations where, formerly, it was locally abundant during the 1970s, but in 2002, CPUE was the highest on record since 1984. The CPUE for all shrimp species approaches the abundance of the early 1980s for the survey series. Therefore, recent survey results support the notion that pandalid shrimp, as a group, are showing signs of regaining importance in the community structure of the GOA. Recent increases in shrimp populations are directly linked to colder conditions as indicated by the PDO (<http://tao.atmos.washington.edu/pdo>) since 1998. Sustained high population abundance of pandalid shrimp, as a group, would require a continued shift to colder ocean conditions (Anderson 2000). Along with

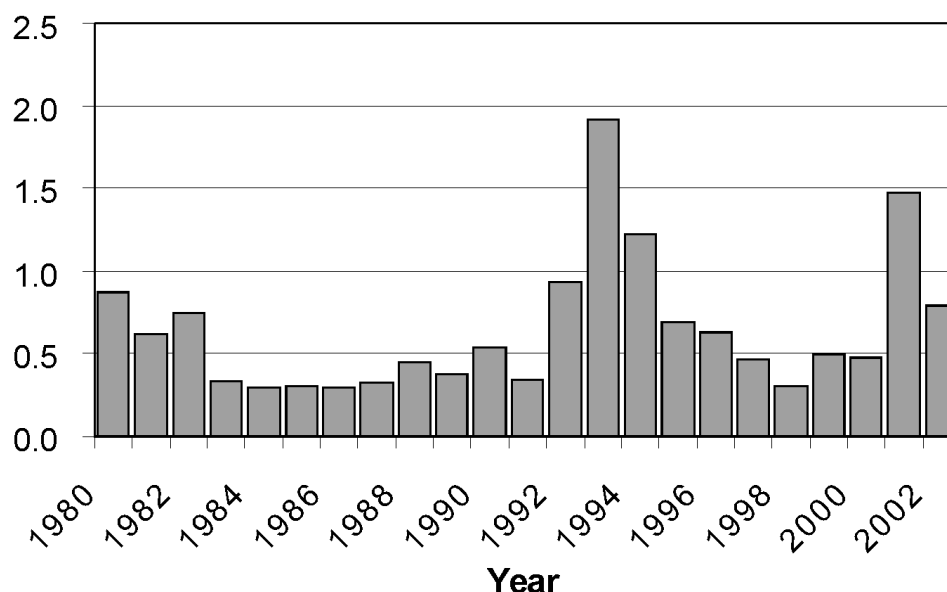
favorable oceanographic conditions to allow strong recruitment of shrimp, there will also need to be declines in predation pressure. These principle factors are important in determining future pandalid population trends and possibly trends in other species abundance, as well (Anderson 2003).

#### Crabs

Hecate Strait, British Columbia, is at the southern end of the Alaska downwelling system (Ware and McFarlane 1989) and the GOA, and has the largest B.C. population of Dungeness crab (*Cancer magister*). In contrast to the Dungeness crab populations in the California Current System, this B.C. population does not appear to have 8- to 10-year cycles in abundance, but depends on sporadic recruitment events such as occurred in the early 1990s (Fig. A3.7). Landings per unit of effort (t vessel-day<sup>-1</sup>) declined to a minimum in 1998, coincident with the warm conditions of the large El Niño Southern Oscillation event, but have been increasing with the cooler conditions since 2000. This fishery has no catch quota limits, but is managed using a combination of size, sex (males only), and season restrictions. The unit of effort used here (vessel days) does not account for potential increases in fishing power which may have occurred due to the rise in the number of traps per vessel.



**Fig. A3.6** Three-year average catch per unit effort (CPUE) (kg km<sup>-1</sup> trawled) of pandalid shrimp in the Gulf of Alaska (GOA) small mesh survey, 1973–2002 (Anderson 2003).



**Fig. A3.7** Hecate Strait, British Columbia, landings per unit of effort (t vessel day<sup>-1</sup>) of Dungeness crab (*Cancer magister*) from 1980–2003.

### A3.5 Fishes

#### Pelagics

##### Pacific herring (*Clupea pallasii*)

Pacific herring are distributed generally around the perimeter of the North Pacific, from the Yellow Sea in Asia, to southern California in North America (Haegele and Schweigert 1985). Since herring are intertidal spawners, they are dependent on suitable inshore habitat for at least a part of their life cycle. Pacific herring are spring spawners throughout the range, laying adhesive eggs on available substrata and hatching free-floating larvae within 2–3 weeks, depending on ambient water temperature. Juveniles spend their first summer in inshore waters feeding on copepods, then migrate offshore to join immature and adult stocks during the fall of their first year or late spring of their second summer, at which time they become more dependent on euphausiids. In general, herring migrate back to their spawning areas for the first time at age 3 in the south and age 4, or older, in the north. Herring in the eastern Pacific normally live to ages less than 10 although fish up to age 15, or more, have been taken historically in some areas.

The Alaska Gyre ecosystem supports a number of herring stocks. In the GOA, herring range from the Aleutians to Prince William Sound, with the latter area supporting the largest stock. In southeast Alaska, several stocks are fished on a routine basis, with the most important stocks occurring at Sitka. In British Columbia, there are three major northern migratory stocks (Prince Rupert, Queen Charlotte Islands, and the Central Coast), all of similar relative abundance. The major stock in the GOA occurs in Prince William Sound, with an estimated spawning biomass approaching 170,000 tonnes in the late 1980s (Johnson 2002). The fishery has been conducted with purse seines, drift gillnets, or trawls for fall food and bait. The spring fishery for roe consists of both seine and drift gillnet gear sectors, as well as a wild and pound spawn-on-kelp fishery. As in British Columbia, an extensive reduction fishery occurred throughout southeast Alaska from the 1930s through the mid-1960s when stocks collapsed. The fishery was closed and re-opened as the current roe fishery in 1971.

Since 1974, the fishery catch has averaged 6,000 tonnes annually, with numerous closures since 1994 (Johnson 2002). Survival of young-of-the-

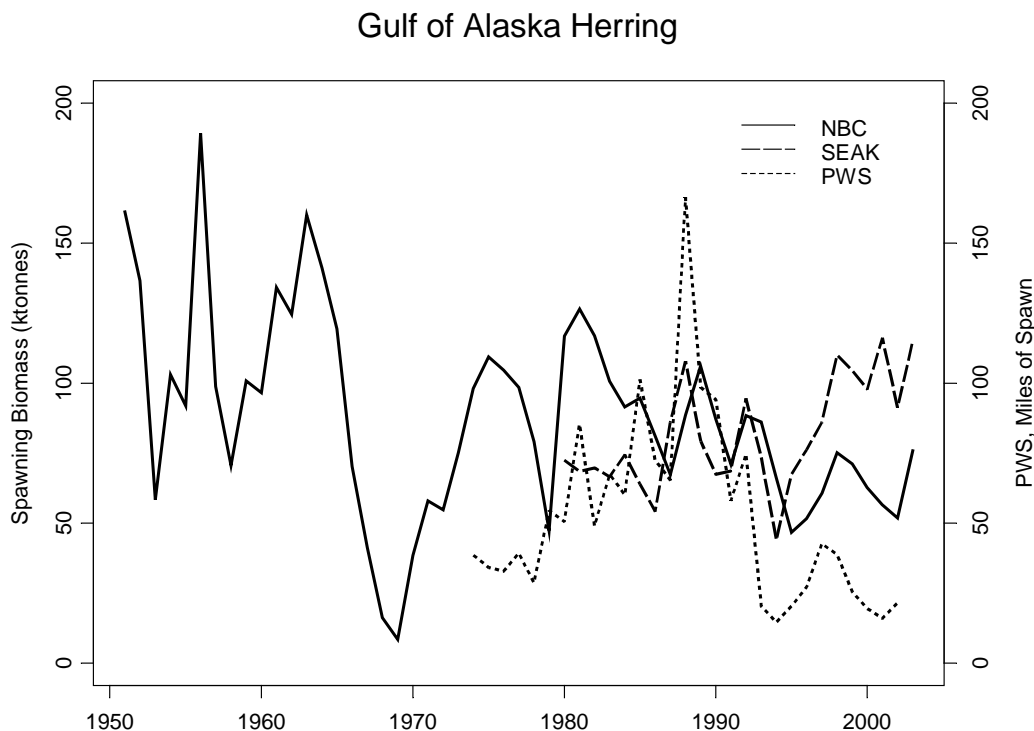
year herring is determined by the amount of energy they store before their first winter (Foy and Paul 1999). There is also evidence of high levels of viral hemorrhagic septicemia, *Ichthyofonus hoferi*, in some years, which has been suggested as the limiting factor in the slow recovery of this stock (Marty *et al.* 1998).

Within southeast Alaska, the major herring stock spawns at Sitka, with abundance fluctuating between 25,000 and 50,000 tonnes, roughly half the entire abundance in southeast Alaska (Fig. A3.8). Other significant runs occur at Kah Shakes, Craig, and W. Behm Canal. Overall, total abundance in the area has remained relatively stable since 1980, with an increasing trend since 1994. The largest fishery occurs at Sitka, using purse seines.

In B.C., abundance of the three major herring stocks has fluctuated since 1980, with no clear

trends in Prince Rupert or the Central Coast (Fig. A3.8; Schweigert 2001). The population in the Queen Charlotte Islands increased to a recent high level in the early 1980s, and has subsequently declined to a near-historic low level with no evidence of recent rebuilding despite the absence of all but the spawn-on-kelp fishery. Overall, combined abundance of these stocks has averaged about 87,000 tonnes since 1951, but has declined from over 100,000 tonnes in the early 1980s to about 60,000 tonnes in recent years.

It has been noted by Williams and Quinn II (2000b), Zebdi and Collie (1995), and others that herring populations in the GOA are closely linked to environmental fluctuations, particularly SST. Herring stocks in southeast Alaska and B.C. were found to respond in opposite directions to temperature inputs although the mechanisms involved remain unclear.



**Fig. A3.8** Estimated combined annual herring spawning biomass at major spawning areas in northern British Columbia (1951–2002), southeast Alaska (1980–2002), and Prince William Sound (1974–2001).

### Capelin (*Mallotus villosus*)

Capelin are distributed along the coastlines of southern British Columbia to Alaska (Nelson 2003), in cool slope waters (Hollowed *et al.*, in review). Capelin spawn in spring in intertidal areas at the age of 3–4 (11–17 cm) and most die after spawning (Pahlke 1985). Fast-growing capelin mature earlier than slow-growing capelin. Capelin catches in the Alaska Department of Fish and Game (ADF&G) small mesh survey in the northern GOA decreased in the 1980s (Fig. A3.9; Piatt and Anderson 1996; Anderson and Piatt 1999). Capelin have remained at relatively low levels of less than  $0.1 \text{ kg km}^{-1}$ , well below their historic peak abundance of  $16.8 \text{ kg km}^{-1}$  in 1980 (Anderson 2003). The decline in capelin abundance has been attributed to an increase in water temperature (Piatt and Anderson 1996; Anderson *et al.* 1997). Capelin are also captured incidentally in the National Marine Fisheries Service (NMFS) Resource Assessment and Conservation Engineering (RACE) bottom trawl survey of the shelf, which may provide an index of abundance (Fig. A3.9). Catches were high in the central and eastern GOA in 1996. However, this survey is not designed to assess capelin, and increases in abundance were influenced by a very few and unusually large catches (Brown 2003).

### Eulachon (*Thaleichthys pacificus*)

Eulachon are distributed from northern California to the Bering Sea. They are anadromous fish that spawn in coastal rivers. Eulachon spawn primarily at the age of 3 and most do not survive after spawning. Very little is known about eulachon, but observer and fishery data suggest that their abundance decreased in the 1980s (Fritz *et al.* 1993). Average eulachon catch in the north GOA ADF&G small mesh survey was 1.9 and  $6.7 \text{ kg km}^{-1}$  during the 2001 and 2002 surveys, respectively (Fig. A3.9). This is the highest level observed for eulachon in the last 30 years. Recent ocean conditions have been optimal for juvenile survival. A major recruitment event of juvenile eulachon was evident in the size frequency data collected in 2002. A strong size mode at around 8 cm fork length was evident in many sampling locations (Jackson 2003). This size mode of eulachon in small-mesh trawl survey catches is seldom observed. High catches were also

recorded in the NMFS RACE bottom trawl survey in 2001, although this survey was not designed to sample these fish (Fig. A3.9).

### Salmonidae

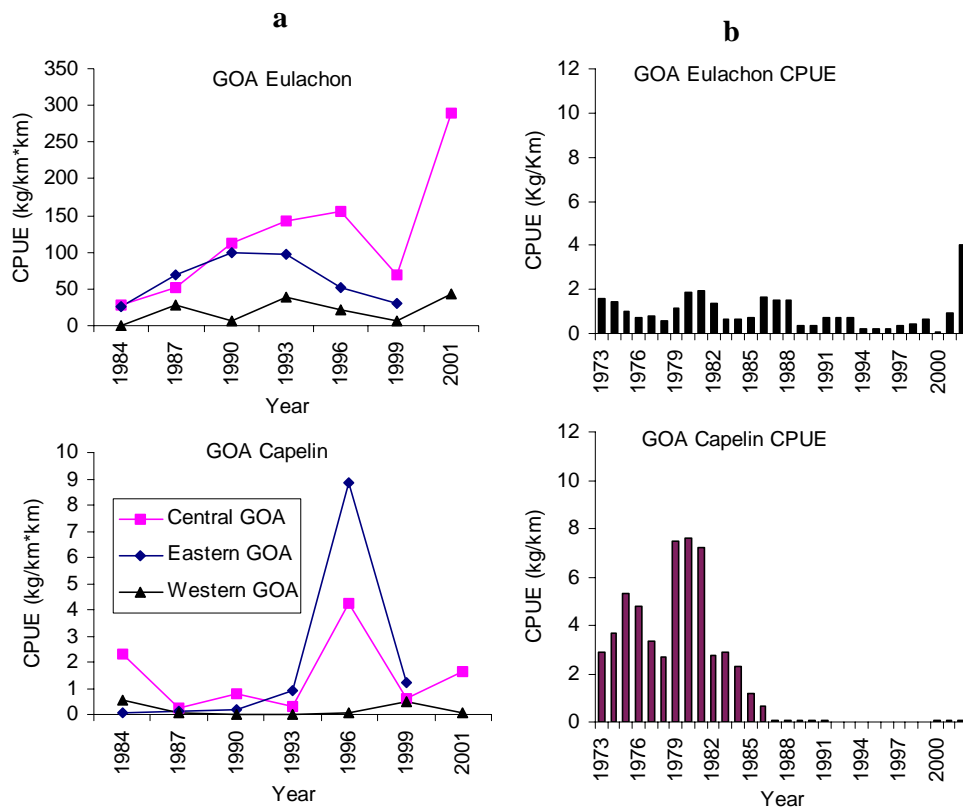
Pacific salmon rear in the GOA and central Bering Sea and are managed in four regions of Alaska: southeast Alaska, central (Prince William Sound, Cook Inlet, and Bristol Bay), AYK (Arctic, Yukon, Kuskokwim), and westward (Kodiak, Chignik, and Alaska Peninsula). Salmon distribution throughout the GOA and Bering Sea varies by species and stocks, some of which migrate between the two areas (K.W. Myers, University of Washington, pers. comm.). Pink, sockeye, and coho salmon generally spend the majority of their ocean lives in offshore pelagic waters, bounded by brief periods of migration through coastal areas as juveniles and returning adults.

Pink salmon (*Oncorhynchus gorbuscha*) are distributed from California to Russia and Korea. They have a 2-year life cycle that genetically separates odd and even year pink salmon. Pink salmon spawn between June and October in intertidal zones or in streams, within a few miles of the coast. Eggs hatch in winter or spring, and fry migrate from streams to the ocean. Sockeye salmon (*Oncorhynchus nerka*) are distributed from California to the Bering Sea and Japan. They spawn in late summer to fall, depending on temperature, in streams and tributaries. Eggs hatch in the spring, and fry migrate downstream to lakes where they spend 1 to 3 years before migrating to sea. Sockeye spend 1 to 4 years at sea before returning to their natal streams to spawn and die. Coho salmon (*Oncorhynchus kisutch*) is one of seven species of the genus *Oncorhynchus* native to North America. Coho salmon are anadromous, migrating to the marine environment in the spring as smolts and returning to freshwater in the fall and early winter of their third year to spawn and die. Fry emerge from the gravel in the following spring and usually reside in freshwater for a year before migrating to sea as smolts. Almost all coho spend 18 months at sea before returning to freshwater and therefore, have a 3-year life cycle. Jacks (precocious males), which spend only 6 months in the ocean, are found in

some populations. Adult coho usually weigh from 2–5 kg (45–70 cm in length) and only rarely exceed 9 kg. Coho favor smaller streams and are widely dispersed throughout the GOA ecosystem.

Catches of salmon are used as an index of salmon abundance because estimates of total runs are difficult to attain. Generally, Alaskan salmon stocks have been stable and at high levels of abundance for the last 20 years (Fig. A3.10; Eggers 2003). Asian stocks have shown similar trends, while Pacific Northwest and British Columbia stocks have been at lower levels. During the last decade, there have been some weak runs observed, particularly in certain areas of western Alaska, due to weak recruitment events. Notable examples include Yukon River fall chum, Yukon River summer chum, Yukon River chinook, and Kvichak River sockeye salmon. Observed weak year class strengths, however,

have not been observed for most other Alaskan salmon stocks. Abundance of sockeye salmon in all areas increased from the mid-1970s to the 1980s (Fig. A3.10). Since then the increased abundance has been stable and at high levels. Pink salmon catches have generally been high in all regions in the last decade, and appeared to begin increasing in the late 1970s (Fig. A3.10). Marine survival of Prince William Sound hatchery pink salmon appeared to increase after 1977, but does not appear to have shifted after the 1989 or the 1998 regime shifts (Fig. A3.11). Coho catches have been moderate to high in all regions. Coho fisheries in central and western Alaska are not fully developed due to the late run and lack of processor interest. The coho catch in AYK from 1998 to 2002 has been lower than in the previous decade, but still above catches in the 1960s and 1970s (Fig. A3.10). In northern B.C., the Skeena and Nass River systems support some of the



**Fig. A3.9** (a) Biomass index values of eulachon and capelin as captured incidentally in the National Marine Fisheries Service (NMFS) Resource Assessment and Conservation Engineering (RACE) bottom trawl survey of the shelf (Brown 2003) and (b) 3-year average catch per unit effort (CPUE) ( $\text{kg km}^{-1}$  trawled) of eulachon and capelin in the Gulf of Alaska (GOA) small mesh survey 1973–2002 (Anderson 2003).

largest coho runs in this ecosystem. Indices of coho abundance for this region indicate a moderate decline in abundance from the early 1980s to the mid-1990s (Fig. A3.12), but a dramatic increase in abundance in recent years (J. Sawada, unpub. data). It is believed that reduced survival in the marine environment has been the main determinant of the coho population decline, which has recently ameliorated. Overfishing, changing marine conditions, and habitat perturbations all contributed to coho declines (Bradford and Irvine 2000). Excessive fishing resulted when harvest rates were not reduced quickly enough in response to climate-driven declines in marine productivity. Bradford (1999) also notes that coho survival was highly correlated among geographically adjacent stocks, suggesting that local environmental conditions have a greater influence on coho production than global conditions. However, factors determining larger-scale coho survival are unclear, although Beamish *et al.* (1999) suggest there are evident climatic links.

General trends in salmon production have been attributed to PDO-scale variability (Hare and Francis 1995), ocean temperature (Downton and Miller 1998), and regional-scale SSTs (Mueter *et al.* 2002). A period of high Alaskan salmon production, from the mid-1970s to the late 1990s, has been attributed to changes in ocean and atmospheric conditions which increased survival, as well as enhanced hatchery releases (Beamish and Bouillon 1993; Coronado and Hilborn 1998; Mantua *et al.* 1997). The increased production was accompanied by a decrease in average salmon weight at maturity, from 1975–93, which has been attributed to density dependence (Fig. A3.10; Bigler *et al.* 1996; Ishida *et al.* 1993), SST (Pyper and Peterman 1999; Hinch *et al.* 1995; Ishida *et al.* 1995), and sea surface salinity (Morita *et al.* 2001).

Catch by species data were provided by Doug Eggers (ADF&G). A full report (Eggers 2003) of run forecasts and a review of the 2002 season is available at <http://www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmhome.htm#forecasts>.

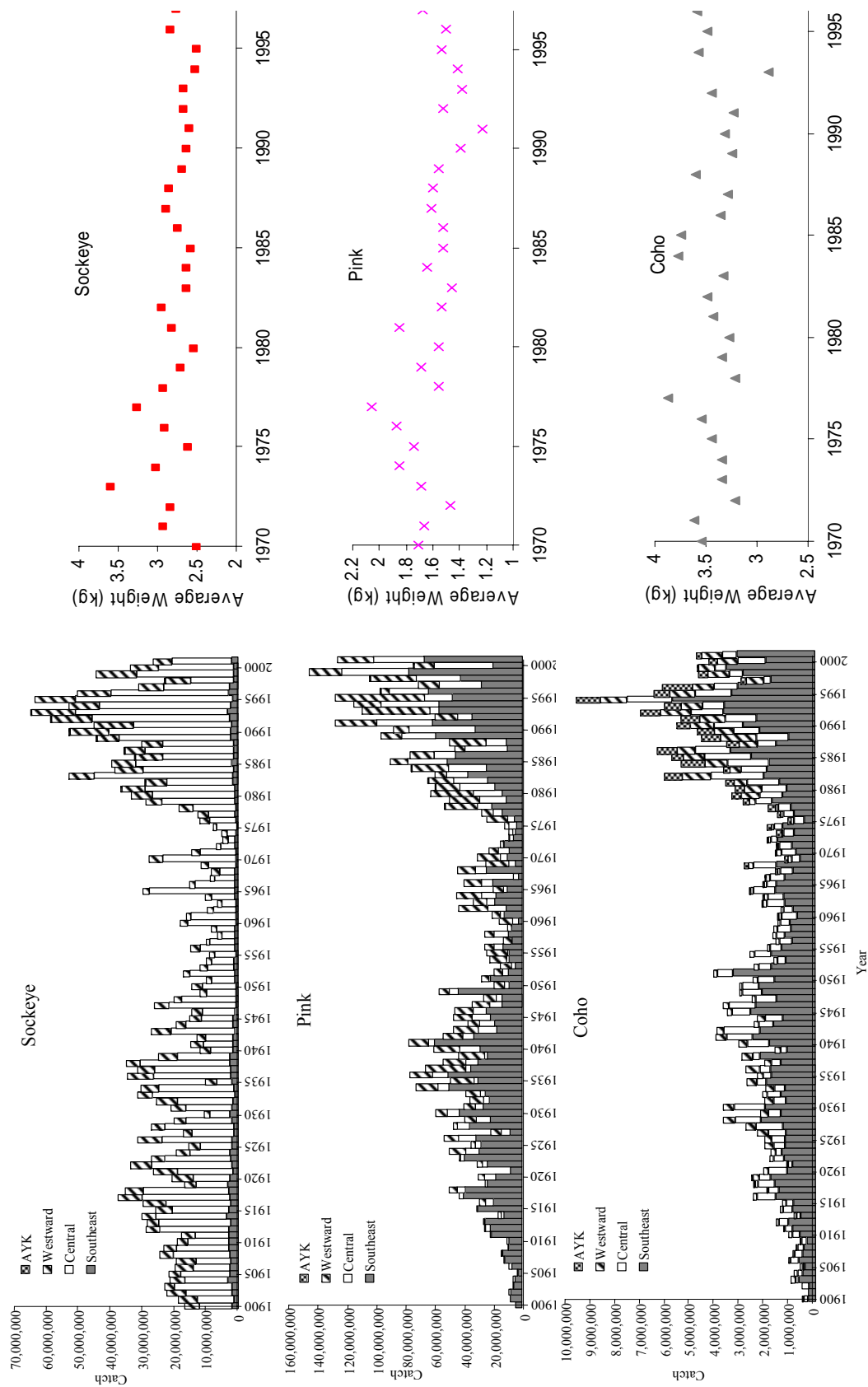
## Gadids and groundfish

### Walleye pollock (*Theragra chalcogramma*)

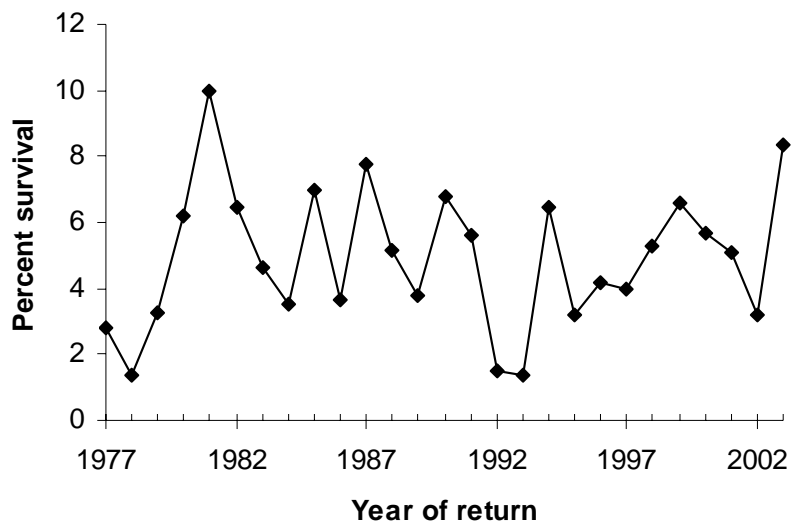
Walleye pollock are semi-pelagic and distributed throughout temperate and subarctic waters of the North Pacific (Wolotira *et al.* 1993). They represent the second most abundant groundfish in the GOA and are exploited in the western/central GOA. Major spawning concentrations occur in Shelikof Strait and near the Shumagin Islands (Kendall *et al.* 1996; DiCosimo and Kimball 2001). Fifty percent of females mature at age 5, or at about 43 cm length. Juvenile pollock are pelagic zooplanktivores and are prey to many fish (Carlson 1995). As pollock age, they become increasingly demersal, piscivorous, and potentially cannibalistic.

Pollock biomass increased from 1969, peaked in 1982, and has since decreased through to 2001 (Fig. A3.13). There was a significant linear decrease in survival (median recruit per spawning biomass anomalies) from 1969–2001. Survival was significantly higher prior to the 1977 regime shift than after the shift (Fig. A3.13). Pollock recruitment is variable, with strong year classes occurring every 4 to 6 years (Dorn *et al.* 2003). Rather than responding to decadal-scale variability, a higher incidence of strong year classes is associated with El Niño north conditions (Hollowed *et al.* 2001).

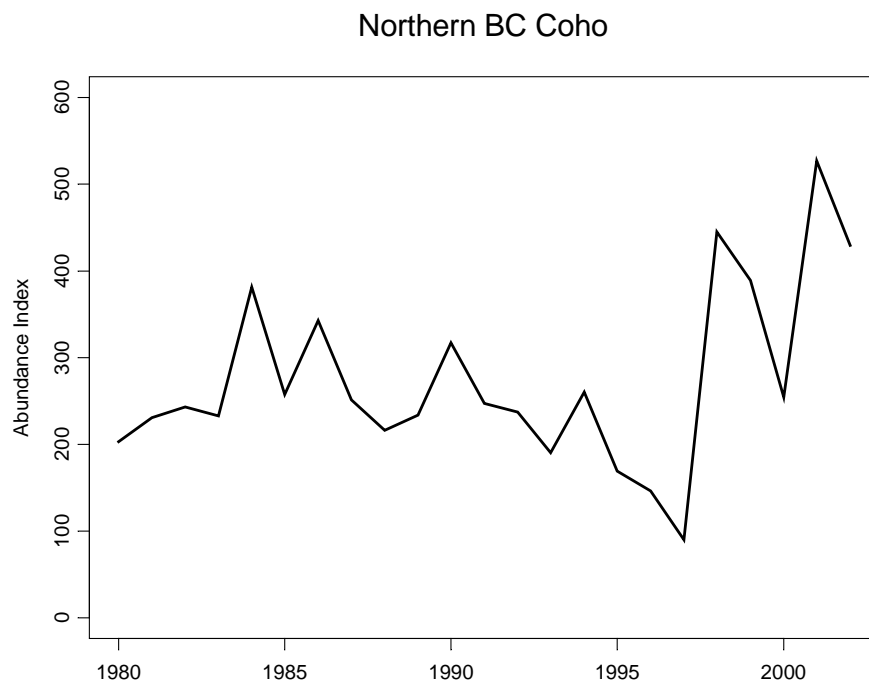
Density-dependent processes may, in part, determine growth, or length-at-age, of pollock in the GOA. Age 4 pollock tend to weigh less and are shorter when there is a strong year class, such as the 1988, 1994, and 1999 year classes (Dorn *et al.* 2003). Pollock lengths at older ages, such as ages 7 and 10, increased from the early 1980s to the present (Fig. A3.13). This increase in length-at-age coincided with a decrease in total biomass of pollock in the GOA, suggesting density-dependent growth. The growth time series does not include estimates prior to the 1977 regime shift, and pollock growth did not appear to respond to the 1989 or 1998 regime shifts. It is, therefore, unclear if the changes in pollock growth in the GOA were responses to decadal-scale climate variations.



**Fig. A3.10** Historical catch and average weight (kg) of sockeye, pink, and coho salmon by area in Alaska. Weight data were obtained from the Alaska Department of Fish and Game website (<http://www.cf.adfg.state.ak.us/geninfo/finfish/salmon/catchval/history/1970-2001s.htm>). Left hand panels are catch; right hand panels are average weights.

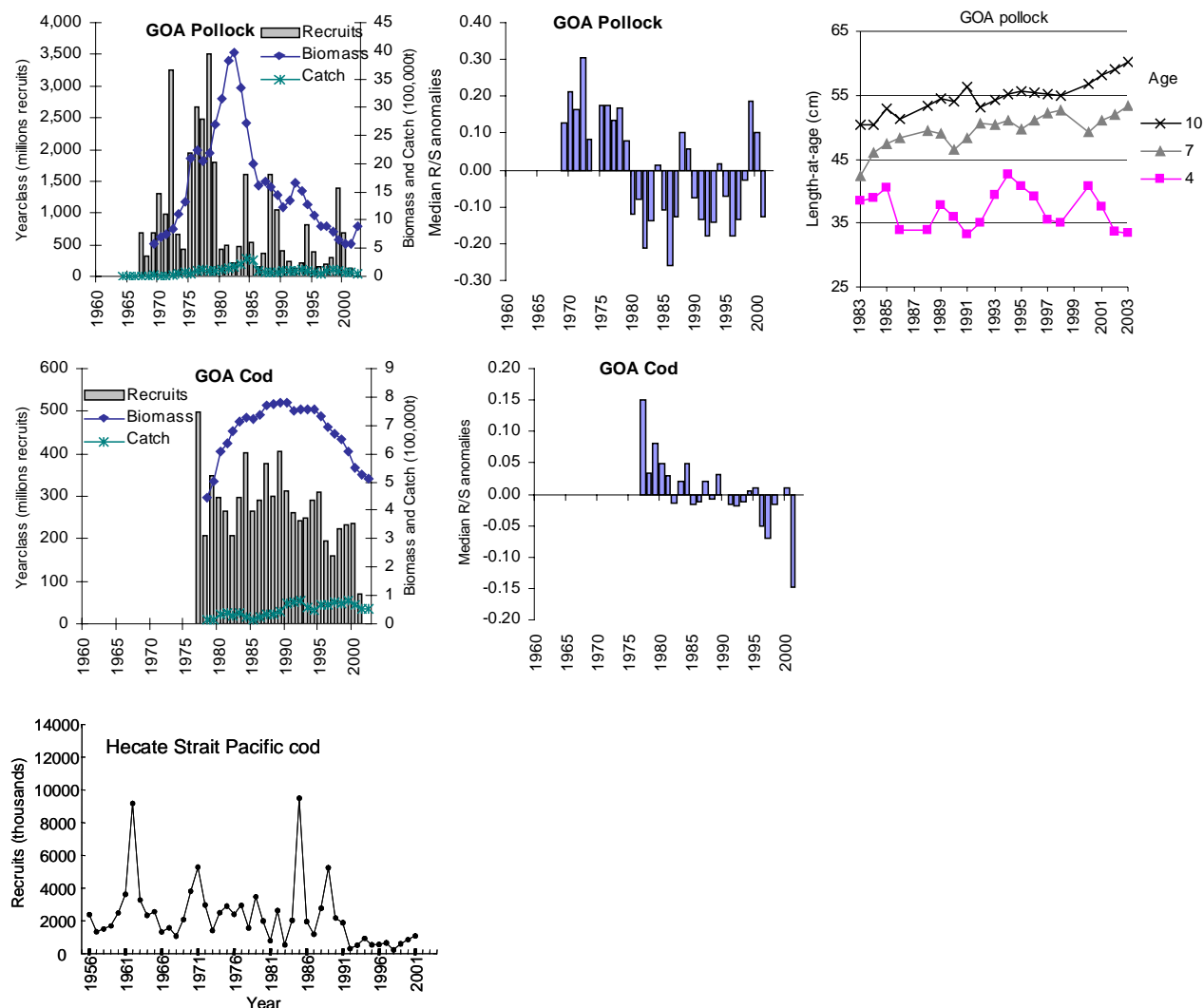


**Fig. A3.11** Marine survival of Prince William Sound hatchery pink salmon by year of return, 1977–2003.



**Fig. A3.12** Index of coho salmon abundance in northern B.C., 1980–2002.





**Fig. A3.13** Gulf of Alaska (GOA) gadid (walleye pollock and Pacific cod) recruits (millions of fish), biomass and catch (100,000 tonnes) in the left panels and median recruit per spawning biomass anomalies (middle panels). The pollock length-at-age data (right panel) was taken from the echointegration trawl survey conducted annually in Shelikof Strait, Gulf of Alaska. Hecate Strait Pacific cod stock recruits (1000s of fish) were estimated by a catch-at-length model (adapted from Sinclair *et al.* 2001).

#### Pacific cod (*Gadus macrocephalus*)

Pacific cod can be found at all depths up to 500 m on the upper slope and continental shelf of the North Pacific, from California to Norton Sound (Bakkala 1984). Pacific cod are demersal fish that spend the winter and spring in deep waters, and migrate to shallower waters in the summer. Fifty percent of females mature at about 6.7 years of age or 67 cm (Thompson and Dorn 2003). Spawning occurs in late winter in relatively small areas near the bottom. Eggs sink to the bottom and are

adhesive (Hirschberger and Smith 1983), and after hatching, larvae occur in the upper 45 m of the water column. Larvae migrate to deeper water as they grow. Growth is rapid within the first year, with Pacific cod reaching lengths of approximately 30 cm. Juvenile Pacific cod consume invertebrates, and become omnivorous as they get larger. Cod move over large areas, resulting in genetically indistinct stocks in the GOA, Aleutian Islands, and Bering Sea (Shimada and Kimura 1994; Grant *et al.* 1987).

The biomass of Pacific cod increased during 1978–90, remained high in the early 1990s, and then decreased to 2001 (Fig. A3.13). There has been a decreasing trend in recruitment since 1990 as well. Median recruit per spawning biomass anomalies indicate that survival linearly decreased significantly from 1977 to 2001. Pacific cod survival appears to vary on the same temporal scale as that of pollock in the GOA. Median recruit per spawning biomass anomalies of GOA Pacific cod and pollock follow similar trends, suggesting that both species are responding to similar large-scale processes. As with pollock, cod have a higher incidence of strong year classes and are associated with El Niño northern conditions (Hollowed *et al.* 2001).

In British Columbia, there are four stocks defined for management purposes: Strait of Georgia, west coast of Vancouver Island, Queen Charlotte Sound and Hecate Strait (adjacent to the GOA). Though there are currently no genetic analyses to verify stock delineation, tagging studies indicate that there is very little movement of Pacific cod between these four areas (Westrheim 1996). The west coast of Vancouver Island and the Hecate Strait stocks have historically supported commercial fisheries and are the two stocks for which stock assessment information is available. Assessments on both stocks indicated a dramatic decline in biomass (tonnes) in the 1990s from historic high levels in the 1980s (Sinclair 2000; Sinclair *et al.* 2001; Starr *et al.* 2002). These declines contributed to nine poor consecutive year classes, beginning in 1990 (DFO 1999). Recruitment estimates are produced by a delay-difference stock production analysis which incorporates research survey data (Sinclair *et al.* 2001; Fig. A3.13).

Recruitment in the Hecate Strait stock has been linked to sea level height, a proxy variable for relative water movement through Hecate Strait (Tyler and Crawford 1991). In the 1990s, this environmental variable suggested that oceanic conditions were unfavorable for recruitment. However, since 1999, this variable has indicated that Pacific cod recruitment may be improving (Sinclair *et al.* 2001).

### Sablefish (*Anoplopoma fimbria*)

Sablefish are distributed from northern Mexico to the GOA, Aleutian Islands, Bering Sea, and to the coasts of Siberia, Kamchatka, and northern Japan (Wolotira *et al.* 1993). They are found at depths greater than 200 m along the edge of the continental slope, shelf gullies, and deep fjords (Sigler *et al.* 2003). Tagging studies suggest that there are two populations: a northern population that is distributed from Alaska to northern B.C., and a southern population that extends from southern B.C. to California (McDevitt 1990; Saunders *et al.* 1996; Kimura *et al.* 1998). The two populations mix in waters off southern B.C. and northern Washington (Sigler *et al.* 2003). Sablefish spawn in the winter at the edge of the continental slope in depths between 300–500 m (McFarlane and Beamish 1983; McFarlane and Nagata 1988). The northern population spawns approximately one month later than the southern population (Sigler *et al.* 2001). Larval fish hatch at about 300–400 m depth, then descend to 1000 m within 18 days after spawning. Within a few days of their descent, larval sablefish begin to ascend and feed on copepod larvae. Juvenile sablefish inhabit shallow inshore shelf waters (< 200 m), and by ages 2–5, move to deeper offshore slope waters.

Recruitment strength appears to be determined at the larval stage (McFarlane and Beamish 1992). Growth of sablefish is rapid in the first few years, then slows appreciably in this long-lived species (Sigler *et al.* 2001; Kimura *et al.* 1998). Males tend to undergo a reduction in growth rate earlier than females. The majority of fish in the fishery are between the ages of 4 and 35, but the oldest sablefish aged to date is 113 years (Beamish and McFarlane 2000).

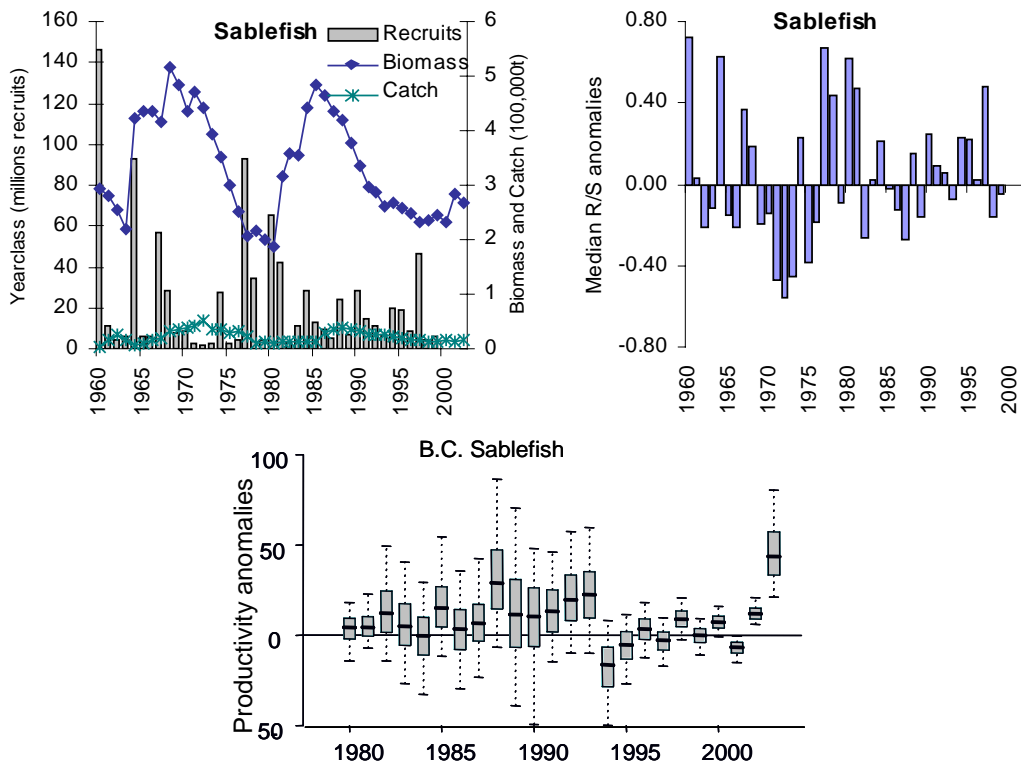
In Alaska, sablefish are assessed in the combined area of the GOA and Bering Sea with an age-structured model that incorporates both fishery and survey catch data (Sigler *et al.* 2003). Sablefish biomass peaked in 1968 and 1985, and was at a minimum in 1963, 1980, and 1997 (Fig. A3.14). Recruitment and survival have been variable but may be related to winter environmental conditions. Strong recruitment tends to occur when there is a

northerly current drift or above-average SSTs (Sigler *et al.* 2001). Strong year classes occurred in 1960, 1977, and 1984, which coincided with strong year classes of other groundfish in Alaska (Hollowed and Wooster 1992). Recent strong year classes include 1995, 1997, and 1998 (Sigler *et al.* 2003).

In Canadian waters, sablefish are caught commercially by trap, longline and trawl fishing gear. Over the last two decades, the commercial catch has ranged from 2,000 tonnes to 5,400 tonnes, and has averaged approximately 4,500 tonnes (Haist *et al.* 2004). The stock is characterized by periods of strong and weak year class success (King *et al.* 2000). Periods with above-average year classes are characterized by intense Aleutian Lows, above-average frequency of south-westerly winds, relatively weak winter downwelling, strong summer upwelling, and above-average abundances of subarctic and boreal

copepods (King *et al.* 2001). From 1977–88, the sablefish population had eight strong year classes, and four below-average year classes (King *et al.* 2000). From 1989–98, there were only two above-average year classes. There is an indication that year class success has improved since 1998 (King *et al.* 2001; Haist *et al.* 2004).

Productivity of the Canadian sablefish stock reflects the trends in recruitment. Estimates of surplus production (Haist *et al.* 2004) exhibit a distinct decadal-scale pattern (Fig. A3.14). From 1980–93, estimates of sablefish productivity are above average. From 1994–2002, these estimates are greatly reduced to average and below-average values. In 2003, the estimate of productivity increases dramatically. Sablefish recruit to the fishery at ages 4 and 5, so the changes in productivity described above correspond to the dynamics of the 1977–89; 1990–98 and the 1999 year classes, respectively.



**Fig. A3.14** Gulf of Alaska sablefish recruits (millions of fish), biomass and catch (100,000 tonnes), and median recruit per spawner biomass anomalies (top two graphs). Productivity anomalies of the Canadian sablefish stock (bottom graph) estimated by a biomass dynamics model by year (from Haist *et al.* 2004). Productivity approximates relative year class success lagged by 4 years (age of recruitment). The median is denoted by the thick horizontal lines, the interquartile range is denoted by the shaded boxes, and the 5th and 95th quantiles are denoted by the whiskers.

## Flatfish

### Arrowtooth flounder (*Atheresthes stomias*)

Arrowtooth flounder are distributed from California to the Bering Sea, and can be found on the continental shelf at the ages of 1 to 4, after which they are found at depths of 100–200 m in shelf and slope waters (Allen and Smith 1988; Martin and Clausen 1995). They are the most abundant groundfish in the GOA. Spawning occurs offshore between September and March, and 50% of females are mature at the age of 5 (Zimmermann 1997; Wilderbuer and Sample 2003), or 47 cm in length (Zimmermann 1997). Juveniles initially consume zooplankton and, as they grow, begin to consume shrimp and small fishes (Wilderbuer and Sample 2003). After arrowtooth flounder exceed 30 cm in length, they are primarily piscivorous, with their main prey consisting of walleye pollock (Wilderbuer and Sample 2003).

Arrowtooth flounder biomass and recruitment were relatively stable during 1961–71, after which they increased to record high levels in 1997 (Fig. A3.15). Median recruit per spawning biomass anomalies, an index of survival, were negative during 1961–69, and strongly positive from 1970–79 (Fig. A3.15). Change point analyses indicate that there was a significant step-change to higher survival after 1968, a significant linear decrease in survival during 1968–97, and minor, but significant, step-changes in 1979 and 1989. This suggests that arrowtooth flounder survival responds to decadal-scale variability. Recruitment success has been linked to improved transport to nurseries in El Niño years (Bailey and Picquelle 2002). Arrowtooth flounder length-at-ages 3–7 did not appear to change between the 1980s and the 1990s, although sample size in the 1990s was small (Fig. A3.15; Turnock *et al.* 2003).

### Flathead sole (*Hippoglossoides elassodon*)

Flathead sole and Bering flounder (*Hippoglossoides robustus*) are similar and managed as a single stock (Wolotira *et al.* 1993). Flathead sole are distributed from northern California to Alaska. Adults are benthic, and overwinter near the continental shelf margin and migrate onto the outer shelf in spring. Age and size at maturity are

unknown, but spawning occurs in spring near the continental margin (Walters and Wilderbuer 1997). Eggs are pelagic and larvae are planktonic, occupying shallow waters where they consume zooplankton. Flathead sole recruit to the fishery at age 3. Adult flathead sole consume primarily benthic invertebrates.

The time series of flathead sole in the GOA is short, beginning in 1981. Therefore, it is difficult to determine if flathead sole respond to decadal-scale climate variability. Their biomass increased from 1984–96, and has declined in recent years (Fig. A3.15). Median recruit per spawning biomass anomalies, indicative of survival, were higher prior to 1988 than in following years, however, the difference was insignificant (Fig. A3.15). Strong recruitment of flathead sole in the Bering Sea may be linked to wind direction that advects larvae to nearshore nursery areas during spring (Wilderbuer *et al.* 2002). However, it is unknown if a similar mechanism is responsible for flathead sole recruitment variability in the GOA.

### Pacific halibut (*Hippoglossus stenolepis*)

Pacific halibut are distributed in coastal waters from California to the northern Bering Sea to Hokkaido, Japan. Halibut spawn off the continental shelf in December through February. They attain sizes of 96 cm at 50% maturity, corresponding to ages 10–12 (Clark *et al.* 1999). Eggs and larvae are pelagic for approximately 6 months, after which the juvenile halibut, at approximately 35 mm length, settle in shallow waters for 5 to 7 years. Halibut are highly migratory for up to 10 years of age, after which time they are less migratory. The maximum recorded age for a halibut is 55 (IPHC 1998). Female halibut grow faster than male halibut (beginning around age 6) and attain much larger sizes. The largest recorded size for a female is 2.67 m, while males rarely exceed 1.5 m. Recruitment to the fishery begins around age 6, with full recruitment occurring around age 8–10 for females and somewhat later for males. Stock assessment of Pacific halibut is based on an age- and sex-structured model, with length-specific gear selectivity for commercial and survey data, and fit-to-age compositions for both commercial and survey catches (Clark and Hare 2004).

The population dynamics of Pacific halibut appears to respond to decadal-scale climate variability. Halibut biomass in the GOA generally increased after the 1977 regime shift through to the 1990s (Fig. A3.15). In the central GOA (from southeast Alaska to the southwest end of Kodiak Island), halibut biomass peaked in 1994, and has since decreased to a biomass similar to that in 1989. Halibut biomass in southeast Alaska has continued to increase to the present, whereas halibut biomass in B.C. leveled off in 1999. Recruitment appears to have responded to the 1977 regime shift, since it also increased after 1977 in all areas of the GOA (Clark *et al.* 1999). Halibut length-at-age (growth) decreased significantly in the central GOA and decreased slightly in B.C. during this time (Fig. A3.15; Clark *et al.* 1999). The decrease in halibut growth may be density dependent, rather than due to the environment. Both intra- and inter-specific competition may be important since both halibut and other flatfish (arrowtooth flounder and flathead sole) increased in abundance during the same approximate time period (Clark *et al.* 1999).

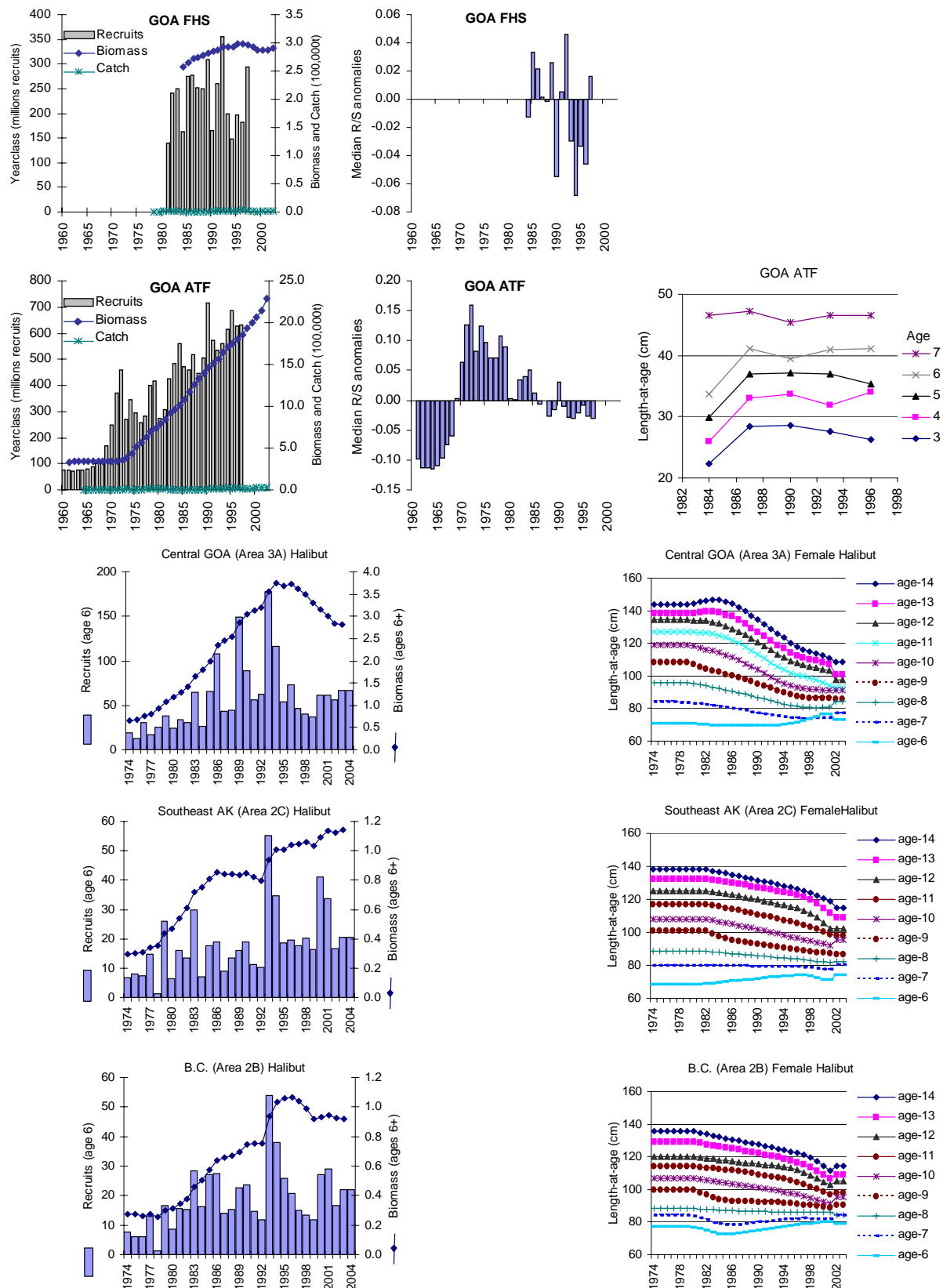
## Rockfish

### Pacific ocean perch (*Sebastes alutus*)

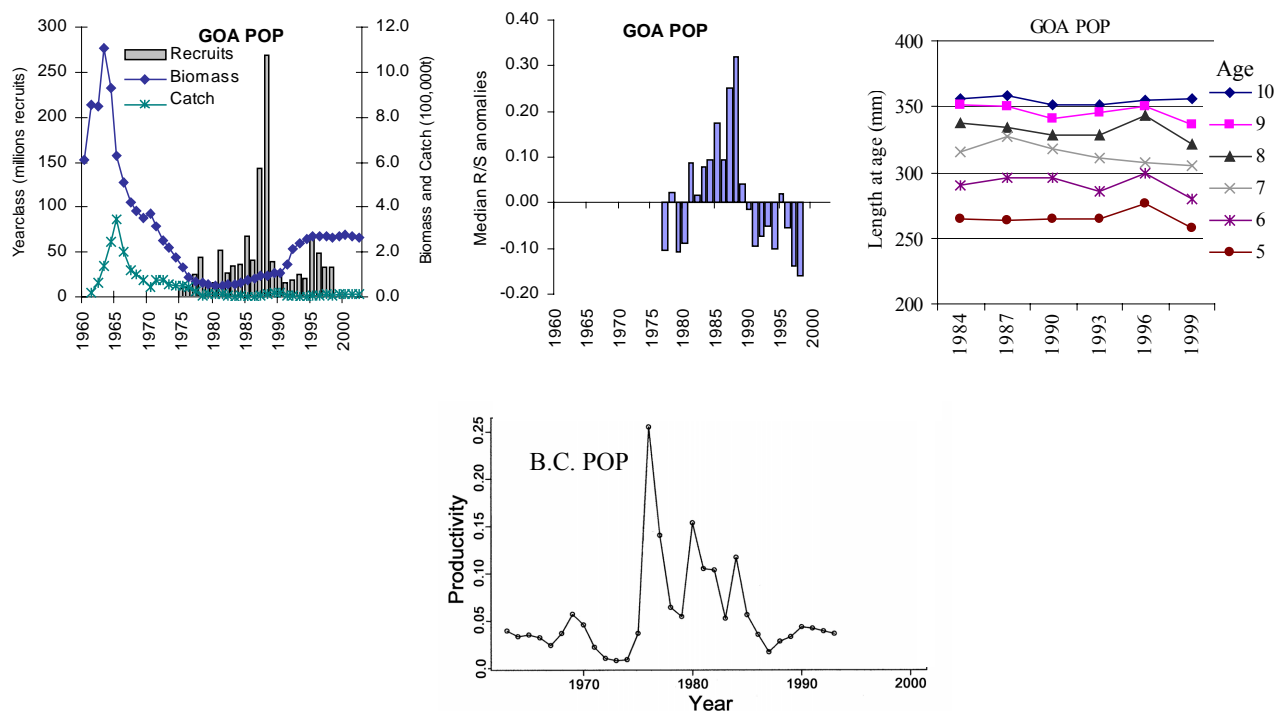
Pacific ocean perch occupy depths from 40–650 m on the outer continental shelf and upper slope, from southern California to the GOA and Bering Sea (Allen and Smith 1988). Fifty percent of females are mature by the age of 7 years, or at approximately 29 cm in length. Pacific ocean perch are viviparous; they spawn in the fall and females release larvae in the spring (Love *et al.* 2002). Larvae are found in surface waters and juveniles settle in nearshore rocky habitats, then progressively move to deeper waters on the shelf. They are long-lived fish that are fully recruited at age 8 and can live as long as 98 years (Heifetz *et al.* 2002). Pacific ocean perch begin recruiting to the fishery at age 7 and are fully recruited to the fishery by age 16. They consume primarily zooplankton throughout their life cycle but also consume myctophids in increasing proportions as they grow larger (Yang 2003).

Pacific ocean perch catches in the GOA declined in the late 1960s to the early 1980s, apparently due to overfishing, and began to increase after 1996 (Fig. A3.16; Hanselman *et al.* 2003). Current stock assessments indicate that biomass decreased to the late 1970s, after which it increased through to the 1990s (Fig. A3.16). Survival of Pacific ocean perch appears to vary on a decadal scale and may be related to changes which occurred during regime shifts. Median recruit per spawning biomass anomalies, indicative of survival, were negative prior to the 1977 regime shift, positive in the 1980s after the 1977 shift, and negative in the 1990s after the 1989 shift (Fig. A3.16). High autocorrelation between catch and recruitment time series also suggests that rockfish in the GOA respond to long-term influences (Hollowed *et al.* 2001). Pacific ocean perch growth, however, does not appear to have changed during the time period of 1984–96; there was a decrease in length-at-age in 1999 relative to other years (Fig. A3.16).

Pacific ocean perch is the most important rockfish species by landed value in catch for British Columbia rockfish fisheries. In Canadian waters, the primary fisheries for Pacific ocean perch occur in three gullies in Queen Charlotte Sound: Goose Island Gully, Mitchell's Gully and Moresby Gully. Other smaller fisheries occur off the west coasts of Vancouver Island and Queen Charlotte Islands. Based on parasite analyses, these five fishery areas are considered to be discrete stocks (Leaman and Kabata 1987). Stock assessments indicate that population dynamics are similar between these stocks (Richards and Olsen 1996; Schnute *et al.* 2001). A catch-at-age model for the Goose Island Gully stock (Schnute *et al.* 2001) indicates a decline in biomass from 1994 through to 2000. This decline has been attributed to relatively low productivity (Fig. A3.16) for year classes since the late 1980s (Schnute *et al.* 2001). If a new regime in 1998 results in improved recruitment for Pacific ocean perch, the resulting age 7 fish will not begin to appear in the fishery until 2005.



**Fig. A3.15** Gulf of Alaska (GOA) flatfish: flathead sole (FHS), arrowtooth flounder (ATF), and Pacific halibut. Left panels: recruits (millions of fish), biomass and catch (100,000 tonnes), middle panels: median recruit per spawner biomass anomalies, right panels: length-at-age (cm). ATF mean length-at-age (cm) is for females sampled in the triennial surveys from 1984–96. Halibut length-at-age data are from the International Pacific Halibut Commission survey samples of females.



**Fig. A3.16** Gulf of Alaska Pacific ocean perch (GOA POP). Left panel: recruits (millions of fish), biomass and catch (100,000 tonnes); middle panels: median recruit per spawner biomass anomalies and productivity; right panel: survey length-at-age (cm) (top three graphs). Goose Island Gully, B.C. Pacific ocean perch productivity was estimated from a catch-at-age model by year class (Schnute *et al.* 2001). Productivity approximates relative year class success lagged by approximately 8 years (age of recruitment).

### Yellowtail rockfish (*Sebastes flavidus*)

Yellowtail rockfish are found throughout the Northeast Pacific Ocean, from southern California through to Admiralty Island, Alaska. The center of abundance is from Oregon to British Columbia. Commercial concentrations are fished from about 100–200 m depth (Lai *et al.* 2003). Yellowtail rockfish attain a maximum size of 70 cm. The oldest recorded age is 64 years. Generally, the size at 50% maturity for females is 37–45 cm (6–11 years old) and for males is 34–41 cm (5–9 years). Yellowtail rockfish begin recruiting to the fishery at age 4 (Lai *et al.* 2003).

In B.C., yellowtail rockfish comprise two stocks: (1) the southern boundary stock, which is off the west coast of Vancouver Island and is considered to be an extension of the northern Washington stock (California Current System), and (2) the coastal stock, which ranges from northwestern Vancouver Island to Alaska (Gulf of Alaska

system). Data for the coastal stock are limited, but the population dynamics are considered to be similar to those observed for the southern boundary stock (Fisheries and Oceans Canada 1999). Poor recruitment in the early 1990s resulted in a severe decline in yellowtail biomass in the mid-1990s. This trend has continued through 2002.

## **A3.6 Higher Trophic Levels**

### **Marine birds**

Seabirds are distributed throughout the North Pacific and include albatrosses, shearwaters, petrels, cormorants, gulls, murres, murrelets, auklets, puffins, and sea ducks. The diet of seabirds varies spatially, temporally, and among species, but includes zooplankton, squid, and forage fish, such as juvenile Pacific herring, smelt, sandlance, walleye pollock, salmon, rockfish, and flatfish.

Populations of many marine birds in Prince William Sound declined between the early 1970s and the early 1990s (Piatt and Anderson 1996; Lance *et al.* 2001). This decline has been attributed to a shift in climate which affected the availability of forage fish to marine birds (Piatt and Anderson 1996; Agler *et al.* 1999). For example, in Prince William Sound, sandlance comprised the majority of seabird diets in the 1970s, whereas gadids were the main prey item in the late 1980s (Kuletz *et al.* 1997). No discernable shifts have been observed in marine bird populations after the regime shifts of 1989 or 1998. However, marine birds are long-lived and population-level responses may lag behind regime shifts. In general, throughout 2001 surface plankton feeding populations (fulmars and petrels) have been stable or increasing, diving piscivorous cormorants appear to have declined, Kittlitz' murrelets are declining throughout the GOA (Kuletz *et al.* 2003), and trends of other marine bird populations vary among areas and species (Dragoo *et al.* 2003). In the northern GOA, marine bird populations are generally declining, while those in southeast Alaska appear to be stable or increasing (Fitzgerald *et al.* 2003).

There is a trend toward earlier breeding times throughout the North Pacific (Dragoo *et al.* 2003). The trend in breeding time could be due to climate changes and timing of spring plankton blooms (Root *et al.* 2003; Dragoo *et al.* 2003). In 2001, marine bird hatch timing was average or early in most areas, except for Storm-petrels in southeast Alaska (Dragoo *et al.* 2003). Also in 2001, the reproductive success of most plankton feeders was generally average to below average, whereas the reproductive success of surface-feeding piscivores (kittiwakes) and diving piscivores (cormorants, murres, murrelets, rhinoceros auklets, and puffins) was average to above average (Dragoo *et al.* 2003).

## **Marine mammals**

### Steller sea lions (*Eumetopias jubatus*)

Steller sea lions are distributed from California to Alaska and Japan (Loughlin *et al.* 1984). There are two distinct populations: the endangered western stock (from east of Prince William Sound

to Russia and Japan) and the threatened eastern stock (from southeast Alaska to California) (Sinclair 2003). The population assessment for Steller sea lions included a number of techniques in the past and is currently accomplished by aerial surveys of non-pups and on-land pup counts (Sinclair 2003).

The western stock declined by about 70% from 1960–89 (Loughlin *et al.* 1992). Since then, the western stock has declined about 3.9% per year, from 1991–2001 (Strick *et al.* 1997; Sease *et al.* 1999; Sease and Loughlin 1999; Sease and Gudmundson 2002). An increase of 5.5% over a large geographic area (eastern GOA to the central Aleutian Islands) was observed in the population in 2002. The western stock population size in 2002, however, is still smaller than it was in 1998 (Sinclair 2003).

Overall, the eastern stock abundance is stable or increasing slowly, although in central and southern California numbers have declined by up to 10% per year (NMFS 1995; Calkins *et al.* 1999; Ferrero *et al.* 2000; Angliss and Lodge 2002). The population in southeast Alaska increased by an average of 5.9% per year from 1979–97 (Sinclair 2003). Within the last decade, the abundance of Steller sea lions in southeast Alaska and British Columbia have increased annually by 2–6% (Sease *et al.* 2001).

### Harbor seals (*Phoca vitulina*)

Harbor seals are distributed from California to the GOA, Bering Sea and Aleutian Islands. They are generally non-migratory, and feed in marine, estuarine, and freshwater (Scheffer and Slipp 1944). Currently the number of stocks in Alaska is a matter of huge debate, however, most scientists believe the previous number (three) is without merit. Recent genetic data and analyses are presently undergoing independent review. The overall harbor seal population in the GOA is much lower than it was in the 1970s and 1980s, but shows some signs of improvement. The number of harbor seals in southeast Alaska is at least steady, if not still increasing (D. Withrow, National Marine Mammal Laboratory, pers. comm.).



### A3.7 Coherence in Gulf of Alaska Fish

Patterns of variation in recruitment and survival of marine and anadromous fishes show synchronicity among stocks, ranging from regional to broad geographical scales. Synchronous strong year classes occur in numerous groundfish populations from California to the Bering Sea (Hollowed and Wooster 1992), with fewer strong year classes in the GOA and Bering Sea than off the United States west coast (Hollowed and Wooster 1995). Strong year classes tend to occur more frequently, and recruitment tends to be larger during the positive phase of the PDO when the Aleutian Low is more intense, and SSTs are above average along the coast (Hollowed and Wooster 1995; Hare and Mantua 2000). Recruitment is moderately to strongly correlated among herring populations within the GOA, while herring in the Bering Sea are distinct from other Northeast Pacific populations (Williams and Quinn II 2000a). Similar to groundfish, recruitment of most herring populations in the GOA and Bering Sea, with the exception of B.C. herring, is enhanced during periods with warm coastal air and SSTs (Williams and Quinn II 2000b). Catches of most salmon species in Alaska tend to show synchronous long-term variations and have generally been high during the recent warm phase of the PDO (Hare and Francis 1995). In contrast, catches along the United States west coast have been low during the same period (Hare *et al.* 1999). Survival rates among different salmon stocks in the GOA and Bering Sea display synchrony at regional spatial scales on the order of hundreds of kilometers, but are mainly independent at larger spatial scales (Peterman *et al.* 1998; Pyper *et al.* 2001; Pyper *et al.* 2002). Survival rates of salmon stocks in Alaska are enhanced when coastal SSTs are warm, while survival rates of B.C. and Washington stocks tend to be reduced during warm periods (Mueter *et al.* 2002).

Cluster analysis and ordination techniques indicate that recruitment patterns of fish stocks in the GOA did not cluster into very cohesive groups (Table A3.1 and Fig. A3.17a), and were characterized by a more continuous distribution in ordination space (not shown). However, recruitment of Pacific ocean perch, thornyhead, and sockeye salmon was well correlated (average correlation:  $\rho = 0.61$ ),

while recruitment of halibut, chum salmon, herring and pollock was moderately correlated ( $\rho = 0.23$ ). Clustering of survival rate series for GOA stocks resulted in at least two cohesive groups of species (Table A3.1 and Fig. A3.17b). The first group included three slope species (Pacific ocean perch, northern rockfish, and shortspine thornyhead) whose survival was relatively strongly correlated ( $\rho = 0.51$ ). Another relatively cohesive group was comprised of the two gadids (Pacific cod and pollock), two flatfish species (Pacific halibut and arrowtooth flounder), and two salmon species (pink and chum salmon). The average correlation among survival rates of these species was 0.38, and their survival rates were uncorrelated or negatively correlated with those of the first group. In particular, arrowtooth flounder survival was negatively correlated with survival of all three species in the first group.

There is evidence for strong positive covariation among certain groups of stocks within the GOA. Most notably, survival rates of pollock and cod were strongly correlated within the GOA. If survival rates (residuals from stock-recruitment models) are indicative of environmental influences, strong covariation in survival is likely to reflect common environmental forcing. Hence a common forcing mechanism appears to drive the survival of cod and pollock within the GOA. Recruitment and survival rates for a number of species in the GOA were positively correlated with gadid recruitment and survival, suggesting common environmental forcing across these species.

### A3.8 Combined Standardized Indices of Recruitment and Survival Rate

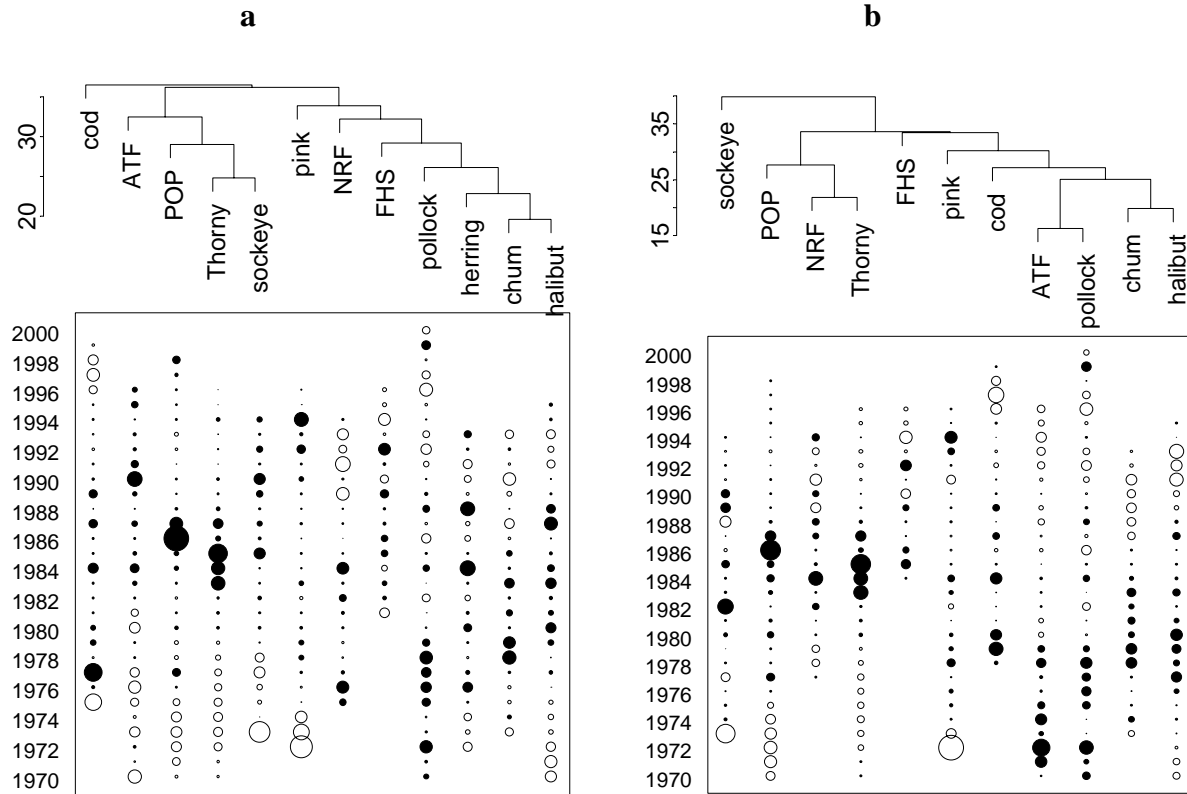
This section provides indices of overall recruitment and survival rate (adjusted for spawner abundance) across the major commercial groundfish species and across major pelagic stocks in the GOA. Time series of recruitment and spawning biomass for demersal fish stocks were obtained from 2002 North Pacific Fishery Management Council (NPFMC) Stock Assessment and Fishery Evaluation (SAFE) reports (2002a and 2002b). Recruitment and spawner abundances for salmon stocks, grouped by region, are based on Peterman *et al.* (1998), Pyper *et al.* (2001, 2002),

and Mueter *et al.* (2002). Herring recruitment series are from Williams and Quinn II (2000b). Survival rate (SR) indices for each stock were computed as residuals from a Ricker spawner-recruit model. A Ricker model with first-order autocorrelated errors was fit to each spawner-recruit series using a generalized least-squares regression of log (recruits-per-spawner) on spawner abundance. Each time series of recruitment or SR indices was standardized to have a mean of 0 and a standard deviation of 1 (hence giving equal weight to each stock in the combined index). Recruitment or SR series were lined up by year class (ocean-entry year for salmon), resulting in matrices of recruitment (or SR indices) by year, with missing values at the beginning and end of many series. A combined

standardized index of recruitment ( $CSI_R$ ) and survival ( $CSI_{SR}$ ) was then computed, following Boyd and Murray (2001). Briefly, all pairwise correlations between time series in a given data matrix (*e.g.*, recruitment series for all demersal stocks in the GOA) are computed based on those years with data for all stocks. The resulting correlation matrix is used to estimate annual means of standardized recruitment across all stocks. This approach allows estimation of annual average indices even for years that have missing data for some (or most) stocks. However, indices based on data for only a few stocks are highly uncertain. Uncertainty in the annual estimated means decreases if the component series are highly correlated (Boyd and Murray 2001).

**Table A3.1** Stocks and stock groups used in analysis by species and region (GOA = Gulf of Alaska; PWS = Prince William Sound), range of year classes and number of years (NR) for which recruitment data were available and number of years (NSR) with both spawner (or spawning biomass) and recruitment data.

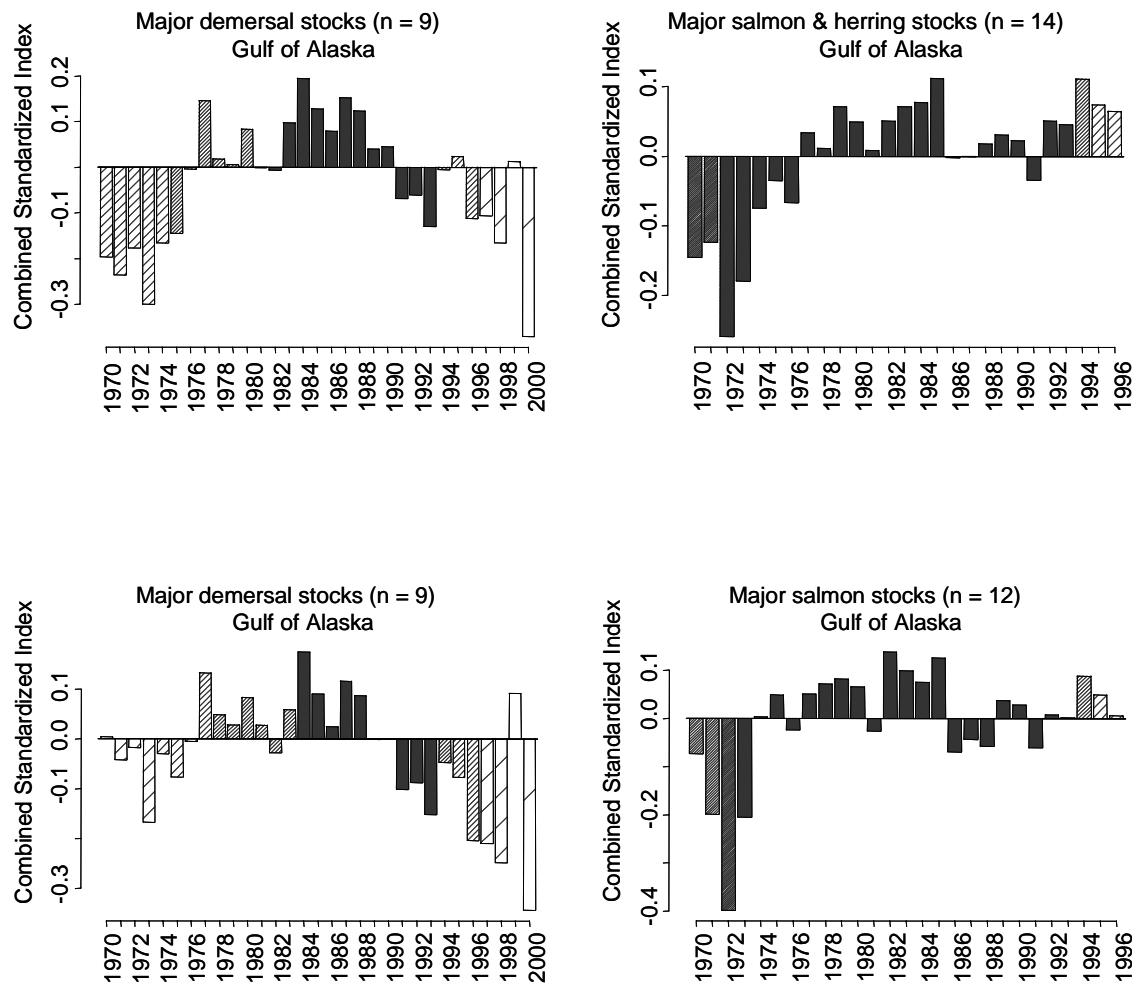
Scientific name	Common name	Region	Year classes	NR	NSR
<i>Atheresthes stomias</i>	arrowtooth flounder (ATF)	GOA	1958-1996	39	36
<i>Hippoglossoides elassodon</i>	flathead sole (FHS)	GOA	1981-1996	16	13
<i>Hippoglossus stenolepis</i>	Pacific halibut	GOA	1950-1995	46	46
<i>Theragra chalcogramma</i>	walleye pollock	GOA	1967-2000	34	32
<i>Gadus macrocephalus</i>	Pacific cod	GOA	1975-1999	25	22
<i>Sebastes alutus</i>	Pacific ocean perch (POP)	GOA	1959-1998	40	38
<i>Sebastes polyspinis</i>	northern rockfish (NRF)	GOA	1975-1994	20	18
<i>Sebastolobus</i> sp	Thornyheads	GOA	1962-1996	35	30
<i>Oncorhynchus nerka</i>	sockeye salmon	western GOA	1952-1995	44	44
<i>Oncorhynchus nerka</i>	sockeye salmon	central GOA	1972-1993	22	22
<i>Oncorhynchus keta</i>	Chum salmon	central GOA	1973-1993	21	21
<i>Oncorhynchus gorbuscha</i>	pink salmon	western GOA	1963-1996	34	34
<i>Oncorhynchus gorbuscha</i>	pink salmon	Kodiak	1963-1997	35	35
<i>Oncorhynchus keta</i>	Chum salmon	western GOA	1963-1993	31	31
<i>Oncorhynchus gorbuscha</i>	pink salmon	central GOA	1972-1997	26	26
<i>Oncorhynchus keta</i>	Chum salmon	PWS	1967-1994	28	28
<i>Clupea pallasii</i>	Pacific herring	GOA	1972-1993	22	0



**Fig. A3.17** Dendrogram of Gulf of Alaska stocks based on hierarchical cluster analysis (average linkage clustering) of pairwise Manhattan distances among standardized (a) recruitment and (b) survival series, and standardized series of positive (filled circles) and negative (open circle) (a) recruitment and (b) survival anomalies for each species, 1970–2000. For species codes see Table A3.1.

The  $CSI_R$  suggests that recruitment of demersal species in the GOA have above-average recruitments from 1977–89, and below-average recruitments in the early 1970s and most of the 1990s (Fig. A3.17). These changes correspond to the regime shifts of 1977 and 1989–90. The  $CSI_R$  for pelagic stocks reflects a strong increase in recruitment around the 1977 ocean-entry year but no apparent change after 1989.

The  $CSI_{SR}$  is more variable but shows similar patterns (Fig. A3.18). A marked increase in survival is apparent in GOA groundfish and pelagic fishes in 1976 or 1977. Survival of demersal stocks was relatively low in the 1990s in the GOA, with the exception of 1999. However, the  $CSI$  is based on few stocks in the late 1990s.



**Fig. A3.18** Combined standardized index of recruitment (top two graphs) and survival rates (bottom two graphs; residuals from Ricker spawner-recruit model) across demersal (graphs on left) and pelagic (graphs on right) stocks or stock groups in the Gulf of Alaska. Solid bars represent years with data for all stocks. Lighter shading corresponds to years with more missing stocks. Series were truncated in 1970 and only years with data for at least two stocks were included (figure adapted from Mueter 2003).

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